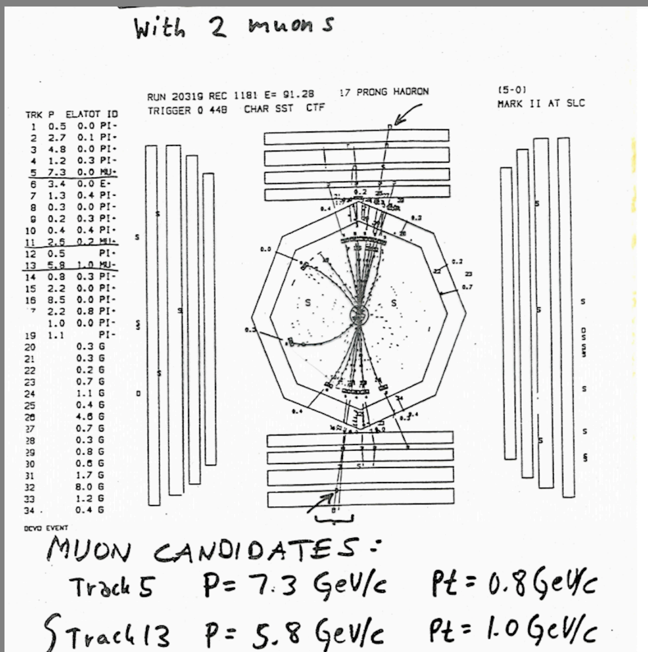
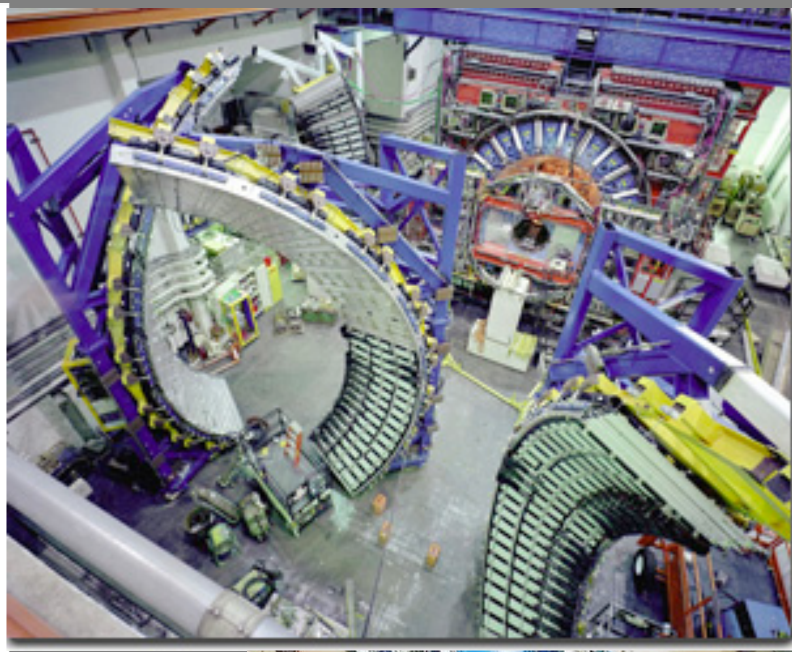
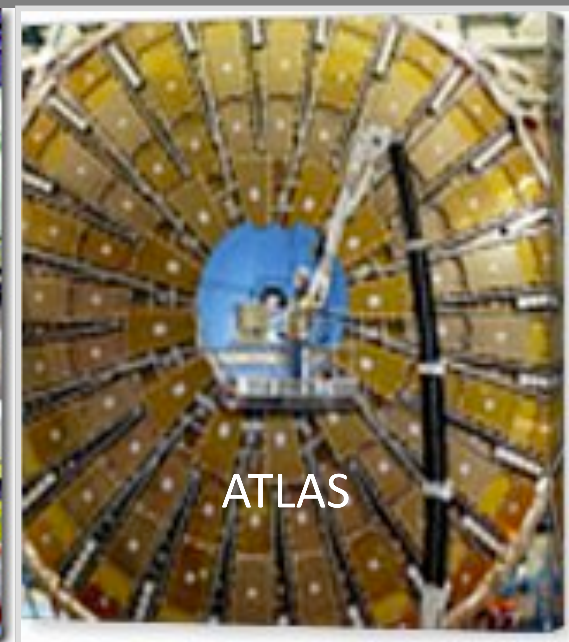
Muons, muon detectors, and muon detectors I have known



MarkII at SPEAR



CDF

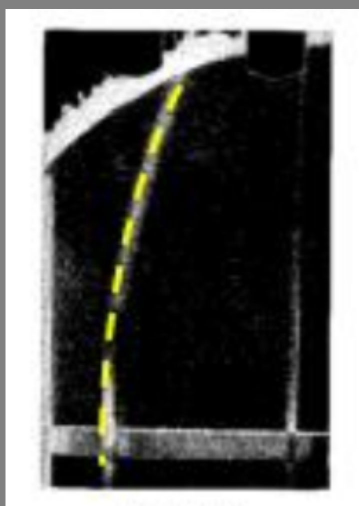


ATLAS NSW

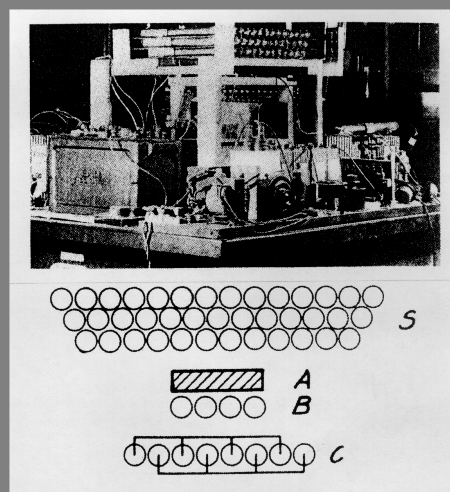
Melissa Franklin -Harvard University-2020

MUON DISCOVERY

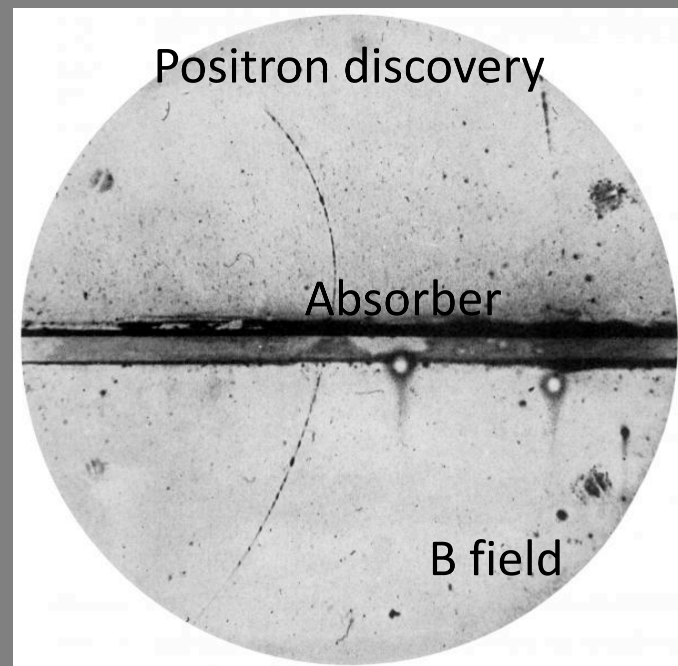
1937 Cloud chamber -
Anderson & Neddermeyer,
Street & Stevenson



Muon candidate track



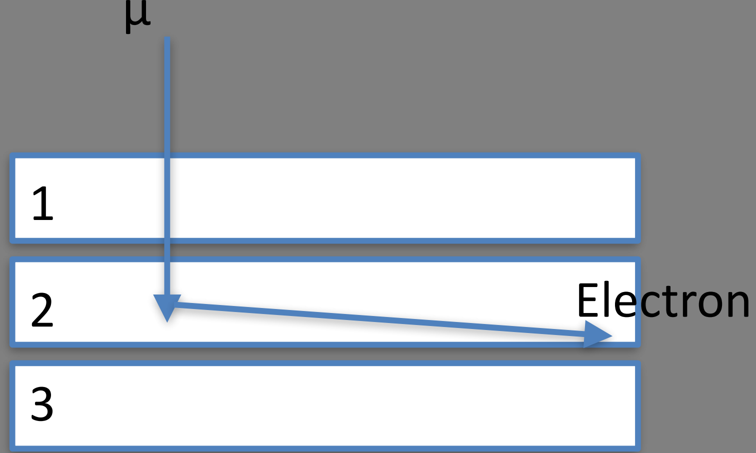
Cosmic ray detector



Same as it ever was: Use cloud chamber as precision tracking and geiger tubes as trigger - measure mass using magnetic field and velocity measurement. mass=qBr/v. Muon has mass between proton and electron, & doesn't shower and doesn't seem to have strong interactions.

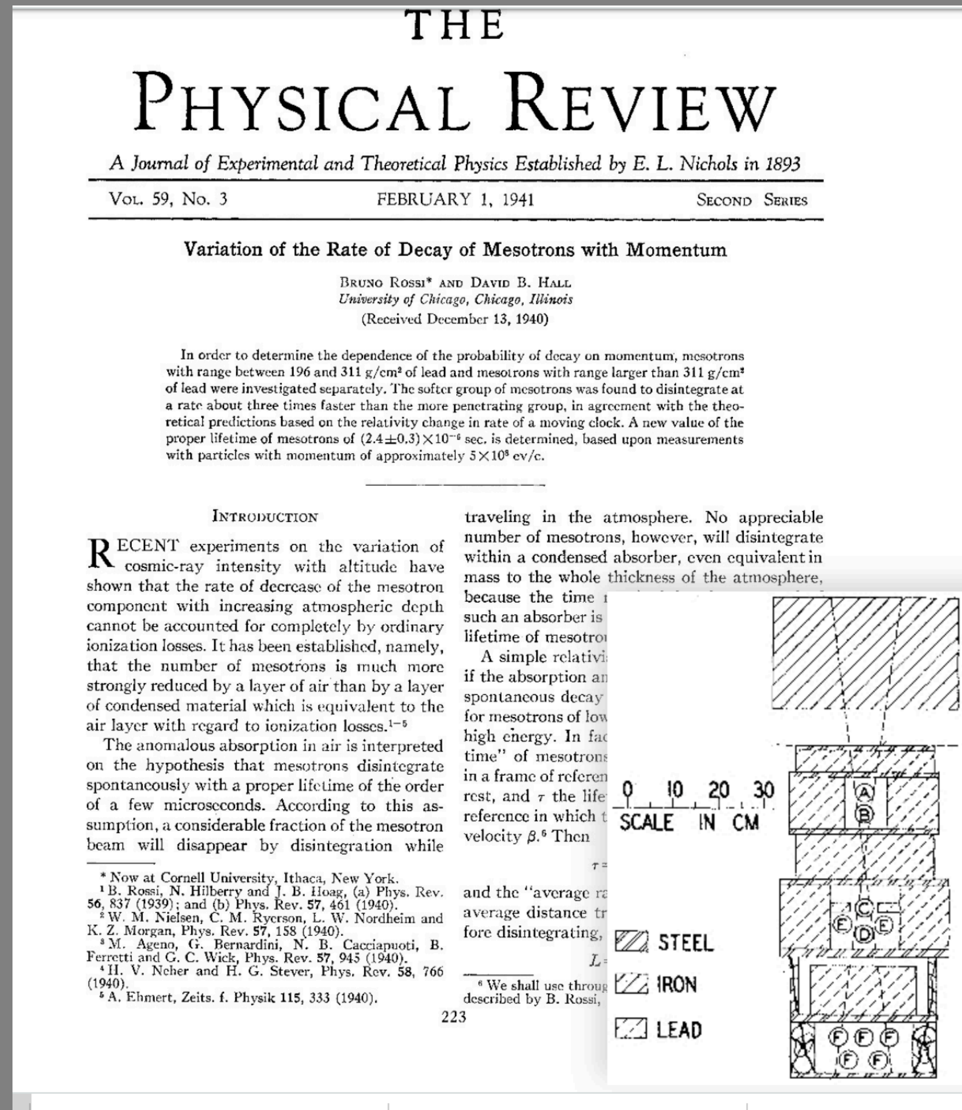
Muon Lifetime

Rossi & Hall 1941



Muon stops, then decays to an electron etc

scintillators: require 1.2 and .not.3



THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 59, NO. 3 FEBRUARY 1, 1941 SECOND SERIES

Variation of the Rate of Decay of Mesotrons with Momentum

BRUNO ROSSI* AND DAVID B. HALL

University of Chicago, Chicago, Illinois

(Received December 13, 1940)

In order to determine the dependence of the probability of decay on momentum, mesotrons with range between 196 and 311 g/cm² of lead and mesotrons with range larger than 311 g/cm² of lead were investigated separately. The softer group of mesotrons was found to disintegrate at a rate about three times faster than the more penetrating group, in agreement with the theoretical predictions based on the relativity change in rate of a moving clock. A new value of the proper lifetime of mesotrons of $(2.4\pm 0.3)\times 10^{-6}$ sec. is determined, based upon measurements with particles with momentum of approximately 5×10^{8} ev/c.

INTRODUCTION

RECENT experiments on the variation of cosmic-ray intensity with altitude have shown that the rate of decrease of the mesotron component with increasing atmospheric depth cannot be accounted for completely by ordinary ionization losses. It has been established, namely, that the number of mesotrons is much more strongly reduced by a layer of air than by a layer of condensed material which is equivalent to the air layer with regard to ionization losses.[1-5]

The anomalous absorption in air is interpreted on the hypothesis that mesotrons disintegrate spontaneously with a proper lifetime of the order of a few microseconds. According to this assumption, a considerable fraction of the mesotron beam will disappear by disintegration while traveling in the atmosphere. No appreciable number of mesotrons, however, will disintegrate within a condensed absorber, even equivalent in mass to the whole thickness of the atmosphere, because the time r

such an absorber is

lifetime of mesotro

A simple relativi

if the absorption a

spontaneous decay

for mesotrons of lo

high energy. In fac

time" of mesotrons

in a frame of referen

rest, and τ the life

reference in which t

velocity β.[6] Then

$\tau =$

and the "average ra

average distance tr

fore disintegrating,

$L =$

* Now at Cornell University, Ithaca, New York.

[1] B. Rossi, N. Hilberry and J. B. Hoag, (a) Phys. Rev. **56**, 837 (1939); and (b) Phys. Rev. **57**, 461 (1940).

[2] W. M. Nielsen, C. M. Ryerson, L. W. Nordheim and K. Z. Morgan, Phys. Rev. **57**, 158 (1940).

[3] M. Ageno, G. Bernardini, N. B. Cacciapuoti, B. Ferretti and G. C. Wick, Phys. Rev. **57**, 945 (1940).

[4] H. V. Neher and H. G. Stever, Phys. Rev. **58**, 766 (1940).

[5] A. Ehmert, Zeits. f. Physik **115**, 333 (1940).

[6] We shall use throug described by B. Rossi,

Time Dilation demonstration video

https://www.youtube.com/watch?v=rbzt8gDSYIM

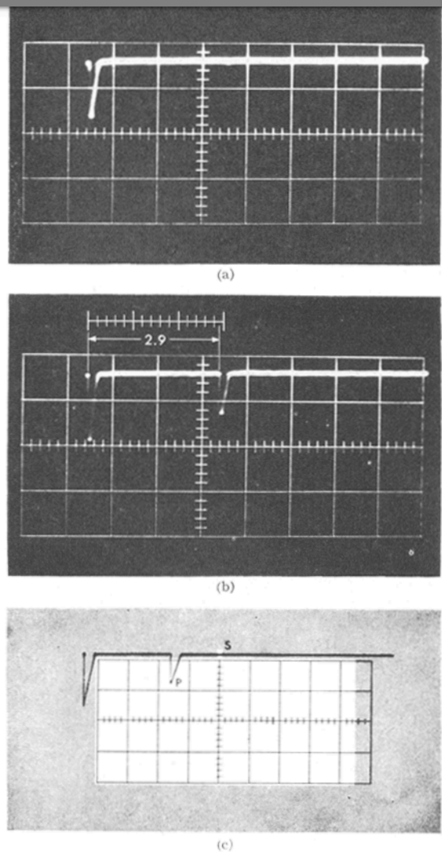


FIG. 4. (a) This photograph shows a single trace caused by a μ-meson traversing the scintillator. Each major division of the time scale is one μsec. (b) This photograph shows a single trace caused by a μ-meson stopping in the scintillator and decaying after 2.9 μsec. The ionization caused by the resultant electron produces the second pulse. (c) The drawing shows the position which the events recorded in 4(b) would have had during the experiment. The undeflected oscilloscope traces were behind the mask (shaded area) during the experiment. Only pulses (like P) from the decay electrons were visible. The small slit (S) in the mask was used to position the oscilloscope trace. A total sweep length of 8.5 μsec was used to detect the decay pulses.

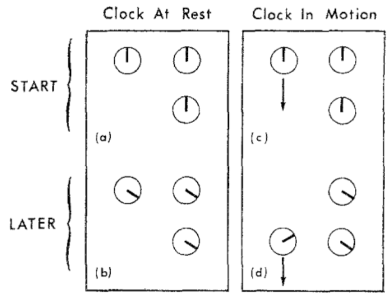


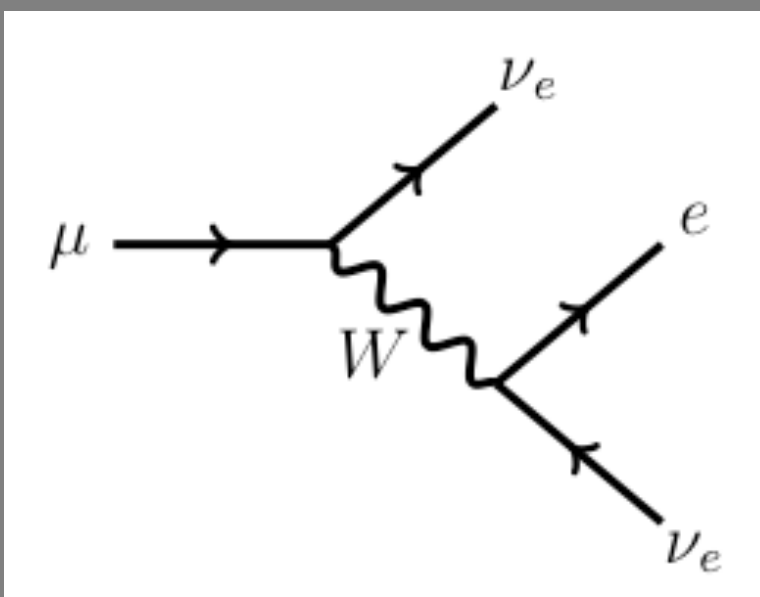
FIG. 1. The behavior of a moving clock. (a) Clocks at rest at time of synchronization; (b) clocks after remaining at rest until a later time; (c) one clock in motion at time of synchronization; (d) the same clock in motion at a later time. Note that the elapsed time read in Fig. 1(d) would be the same even if the moving clocks were started suddenly into motion from rest just after the time of synchronization, and then stopped suddenly just before the time of later observation. The elapsed time as read by the observer depends explicitly on only how long it has been in motion and at what speed relative to the observer, not on its initial or final state of motion, or on any acceleration that it has undergone.

Smith

1963 Frisch and Smith: Time Dilation
The Movie

What we know now

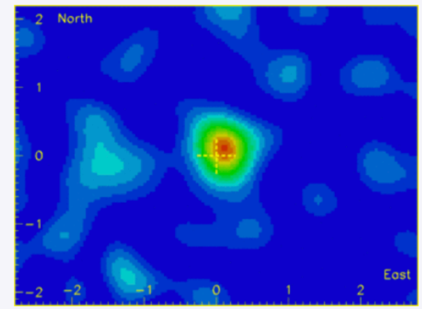
the long lifetime (2.2microseconds) of the muon was surprising presaging a new energy scale - the weak scale.



$\tau = 1/\Gamma$

$$\Gamma \propto \frac{m_\mu^4}{M_W^4} m_\mu c^2$$

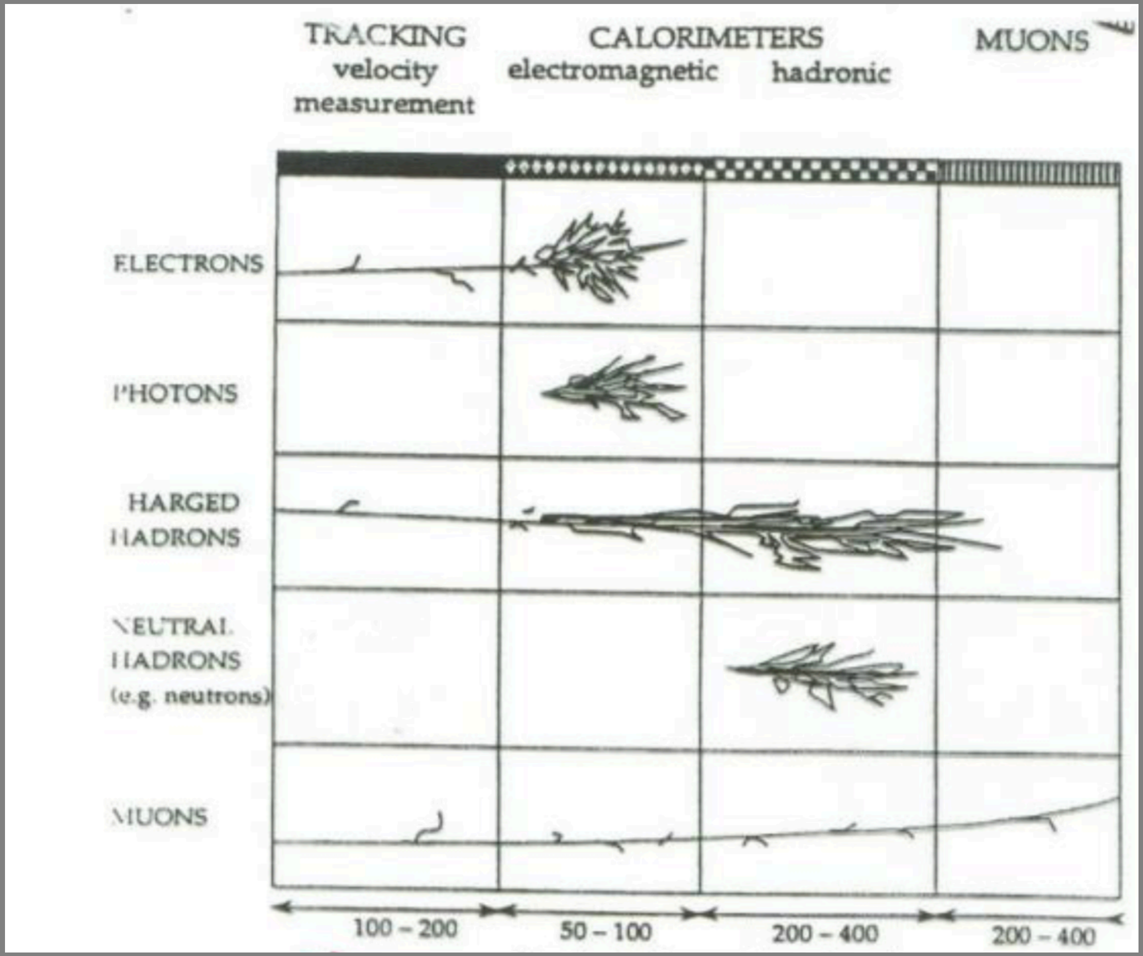
Muon



The Moon's cosmic ray shadow, as seen in secondary muons generated by cosmic rays in the atmosphere, and detected 700 meters below ground, at the Soudan II detector

Composition	Elementary particle
Statistics	Fermionic
Generation	Second
Interactions	Gravity, Electromagnetic, Weak
Symbol	μ^-
Antiparticle	Antimuon (μ^+)
Discovered	Carl D. Anderson, Seth Neddermeyer (1936)
Mass	105.658 3755(23) MeV/c^2[1] 0.113 428 9259(25) Da[1]
Mean lifetime	2.196 9811(22) × 10^{-6} s[2][3]
Decays into	e^-, $\bar{\nu}_e$, ν_μ[3] (most common)
Electric charge	−1 e
Color charge	None
Spin	$\frac{1}{2}$

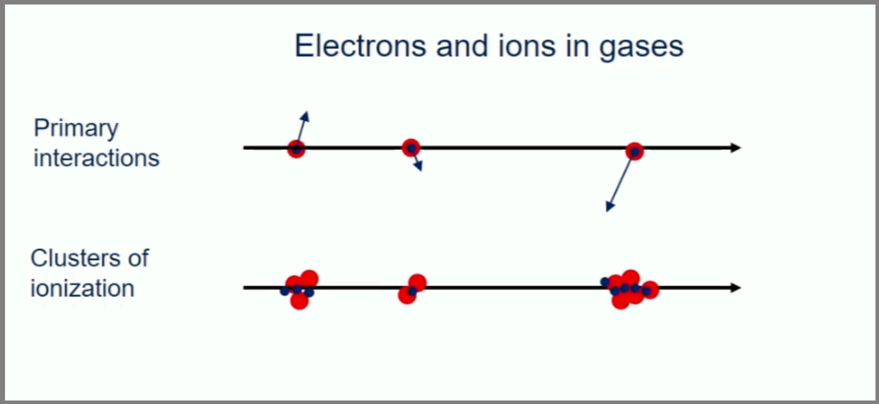
Particle interactions phenomenology

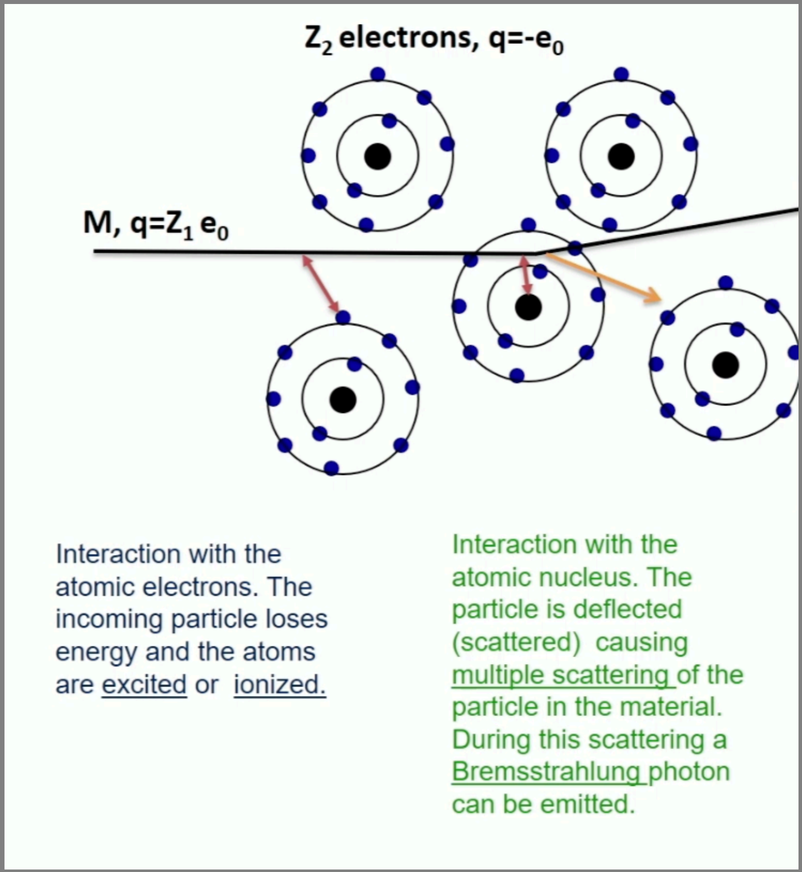


Low ρ. High ρ. High ρ. ?

How does the muon interact in matter

- Muons predominately lose energy through ionization



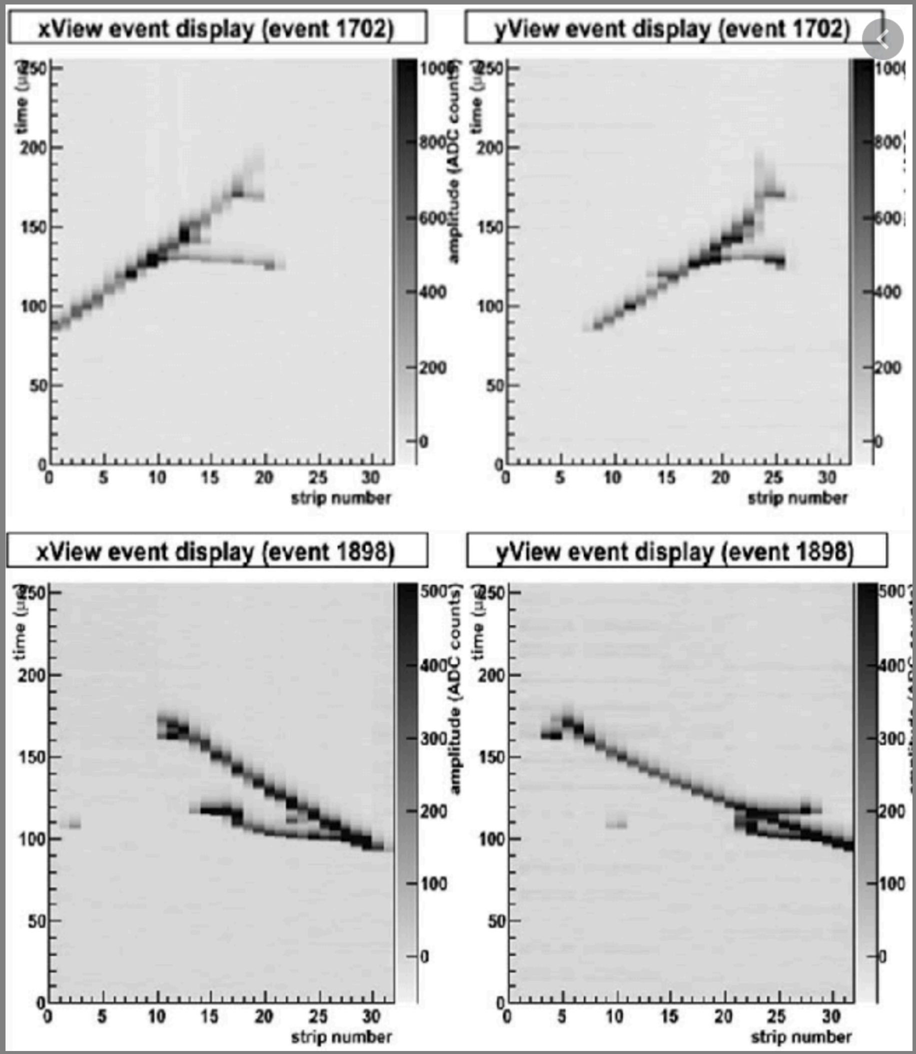


From talk by Werner Riegler - CERN summer school

Delta Rays

Sometimes the electrons that have been ionized have enough energy to ionize again

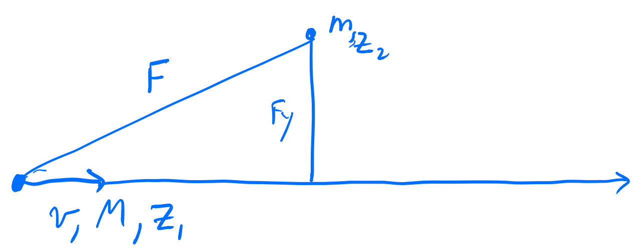
This can make tracking more difficult



Two views of 2 muons with delta rays- TPC

Ionization vs Brehmstraalung?

Easier to impart energy to the electrons



$$F_y \rightarrow \Delta p = \int_{-\infty}^{\infty} F_y(t)\, dt$$

Transferred energy $\Delta E = \frac{(\Delta p)^2}{2m} \propto \frac{Z_1^2 Z_2^2}{2m}$

$$\frac{\Delta E_{electrons}}{\Delta E_{nucleus}} \sim \frac{2 m_{proton}}{m_e} \sim 4{,}000$$

The incoming particle transfers most of its energy to the electrons!

Bethe- Bloch quantum mechanical expression for ionization energy loss by a charged particle

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right],$$

with

$$2\pi N_a r_e^2 m_e c^2 = 0.1535 \text{ MeVcm}^2/\text{g}$$

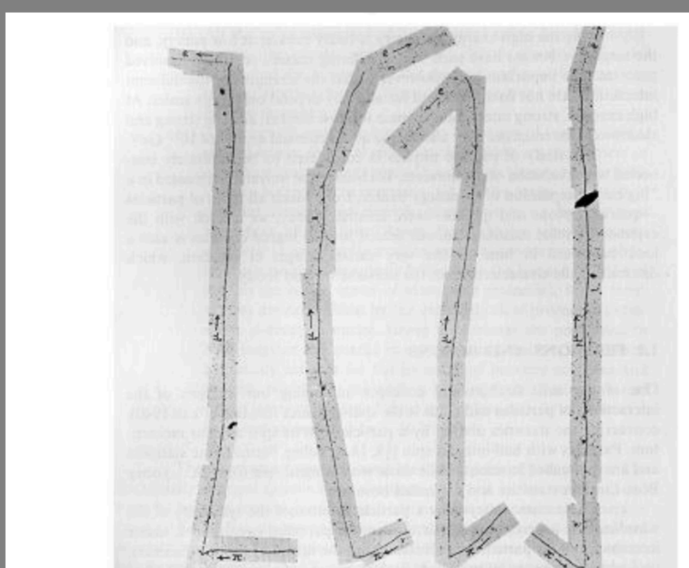
- r_e: classical electron radius $= 2.817 \times 10^{-13}$ cm
- m_e: electron mass
- N_a: Avogadro's number $= 6.022 \times 10^{23}$ mol^{-1}
- I: mean excitation potential
- Z: atomic number of absorbing material
- A: atomic weight of absorbing material
- ρ: density of absorbing material
- z: charge of incident particle in units of e
- $\beta =$ v/c of the incident particle
- $\gamma =$ $1/\sqrt{1-\beta^2}$
- δ: density correction
- C: shell correction
- W_{max}: maximum energy transfer in a single collision.

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[\ln\left(\frac{2 m_e \gamma^2 v^2 W_{max}}{I^2}\right) - 2\beta^2 - \delta - 2\frac{C}{Z}\right.$$

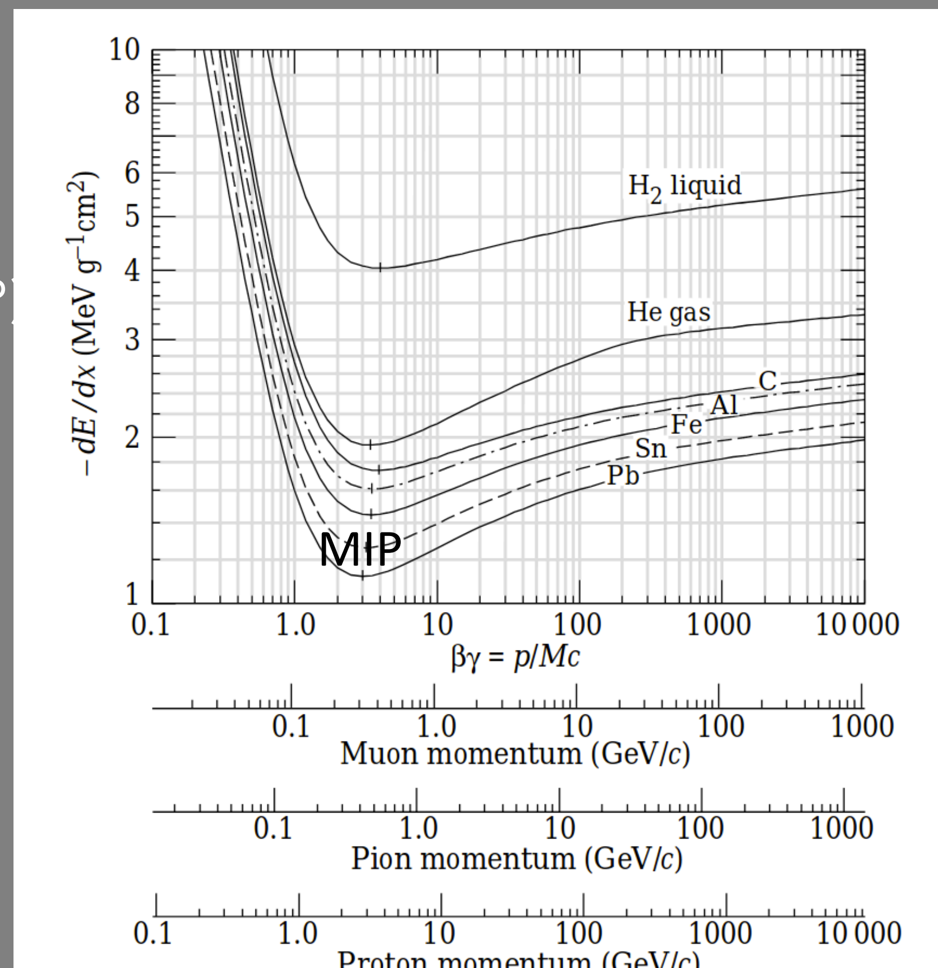
As the velocity goes low
the ionization is high

There is a minimum about 3-3.5 in $\beta\gamma$
This is a Minimum Ionizing particle (MIP)

$1/\beta^2$

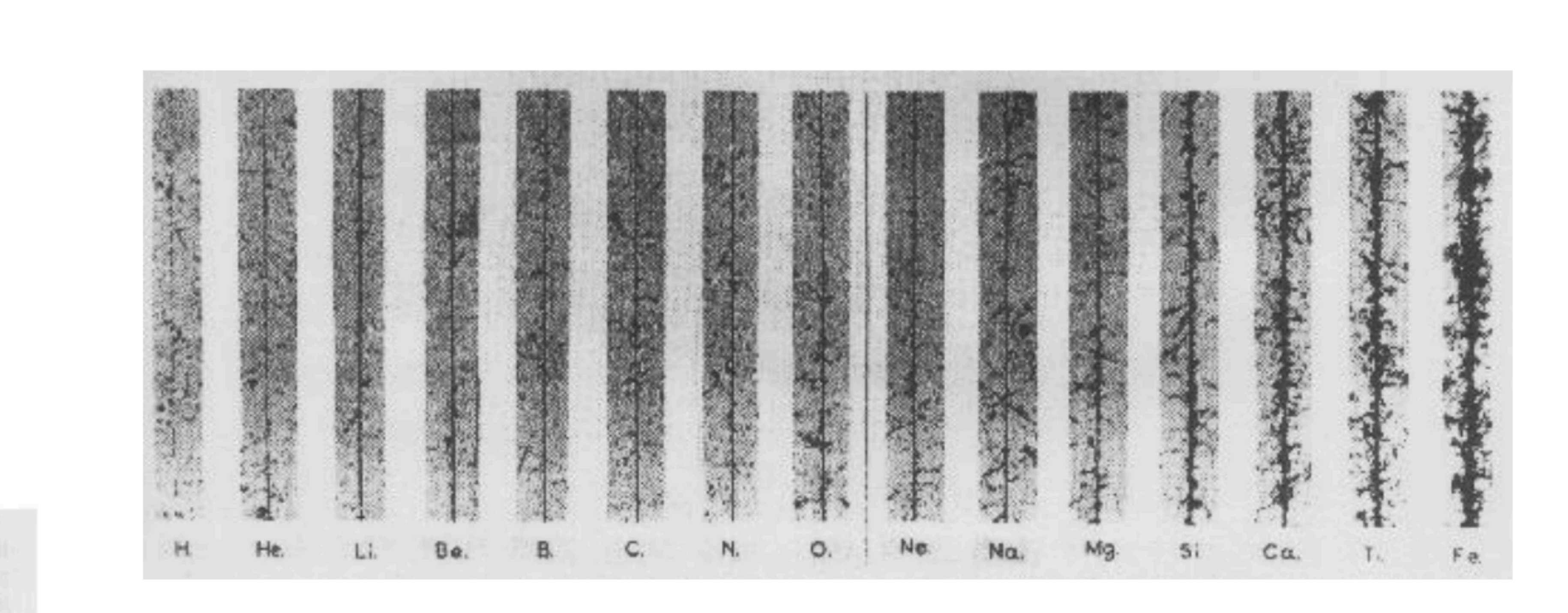


Really $(1/\rho)dE/dx$



Ionization energy loss depends on the square of the charge on the particle

Traversing the detector.



Z^2 1—-4— 9—- 16.———————————————————144 -196———————676

Z/A of the material is pretty constant.

Beth Bloch example

Imagine a MIP muon traversing 1 meter of Fe

Z ~0.5A

From the plot : a MIP (βɣ~3) deposits

dE/dx ~ 1.4 MeV cm^2/gm

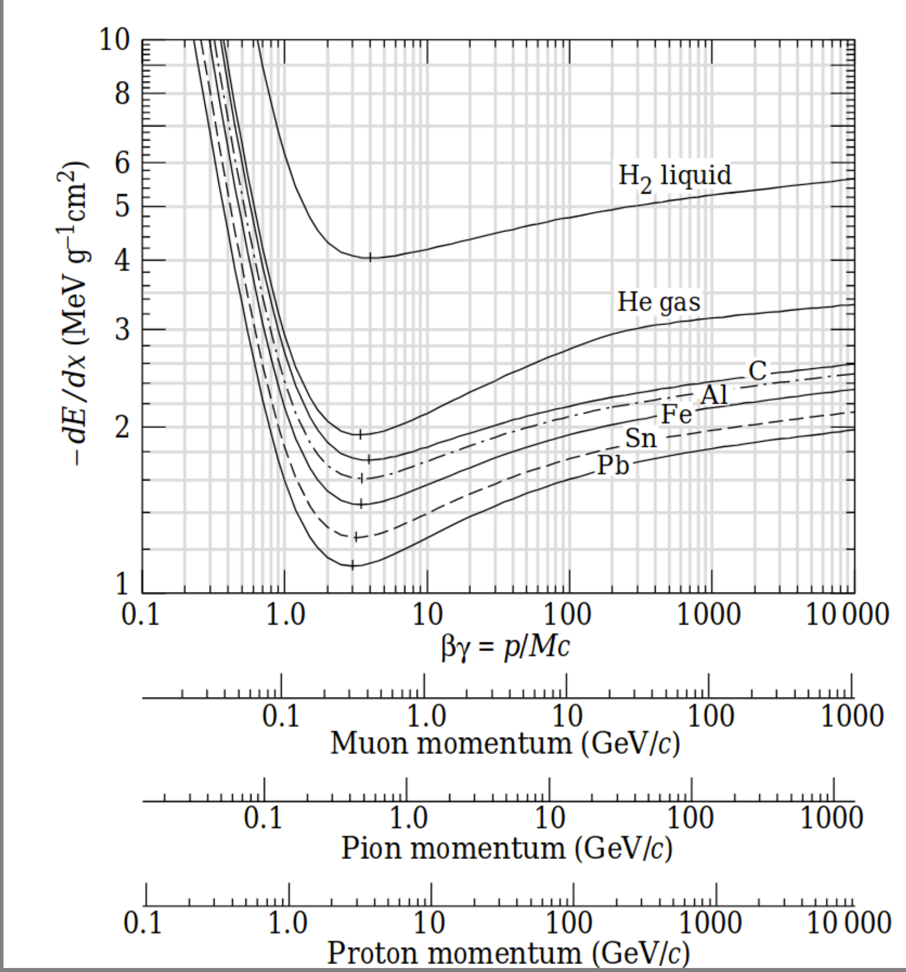
But ρ= 7.87g/cm^3 so dE/dx = 11 MeV/cm

So energy lost over a meter is dE = 1101MeV

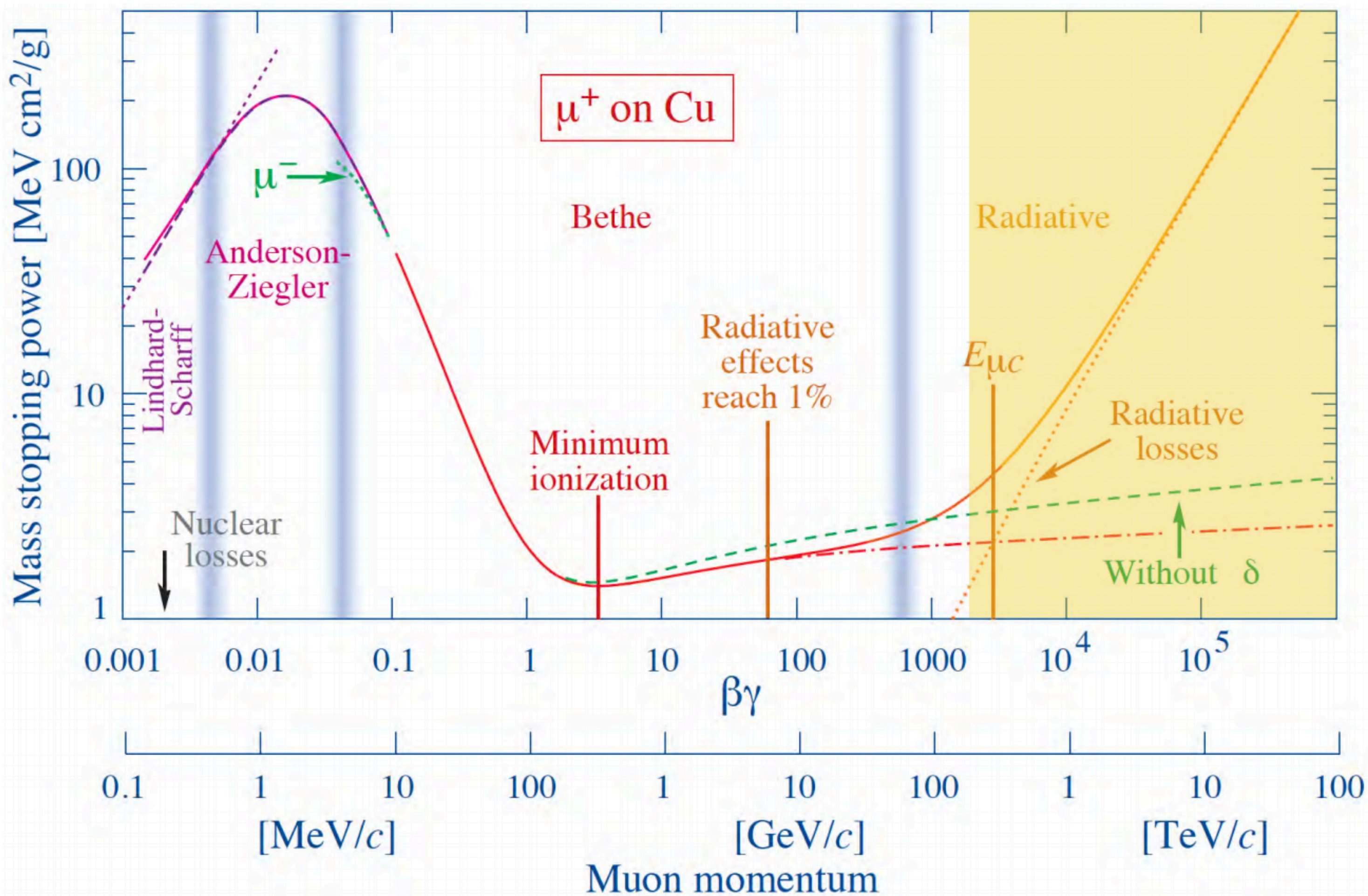
So a 1 GeV muon can traverse 1 meter of steel

of steel!

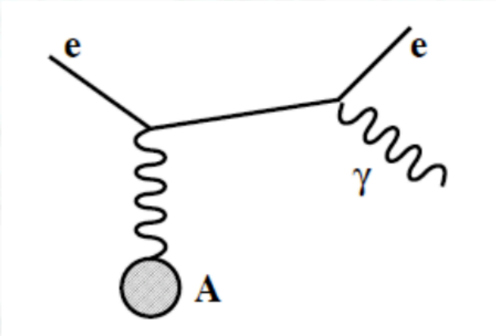
What about a 1 GeV electron or proton?



Bethe Bloch energy loss by ionization - muons on Copper



energy loss by brehmstraalung



$$-\left.\frac{dE}{dx}\right|_{Brems} = 4\alpha N_A \left(\frac{e^2}{mc^2}\right)^2 \ln\frac{183}{Z^{1/3}}\,\frac{Z(Z+1)}{A}\,Q^2 E$$

where: Q, m = electric charge and mass of the particle,
α = fine structure constant
A,Z = atomic number, number of protons of the mate
N_A= Avogardo's number

So for Brehms: energy loss is proportional to E/m^2

Depends on Z(Z+1)/A and the density of the material
Depends on Q^2 and $1/m^2$ of the incoming particle!

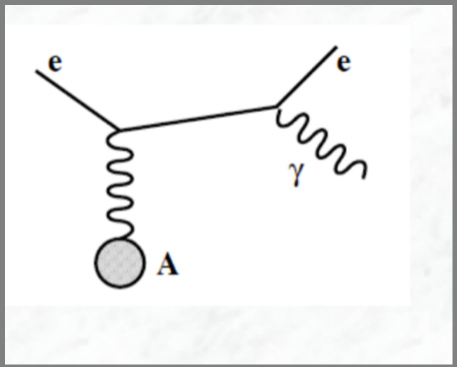
Is linear in E - the energy of the incoming particle
So $(dE_{brehm}/dx)_{muon}/(dE_{brehm}/dx)_{electron} = 1/40{,}000$

Critical Energy E_c Brehm = ionization

$$\boxed{-\frac{dE}{dx}\bigg|_{ion}(E_c) = -\frac{dE}{dx}\bigg|_{brems}(E_c)}$$

On Cu for instance Z=29. E_c(electrons)=19 MeV E_c(muons) = 1 TeV.

So muons do not shower in material and electrons do!



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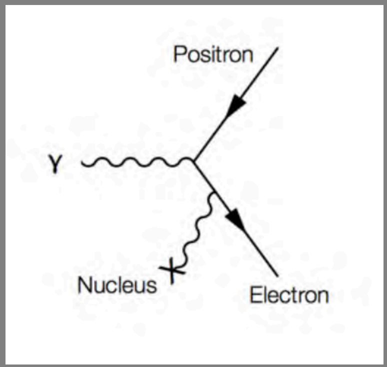

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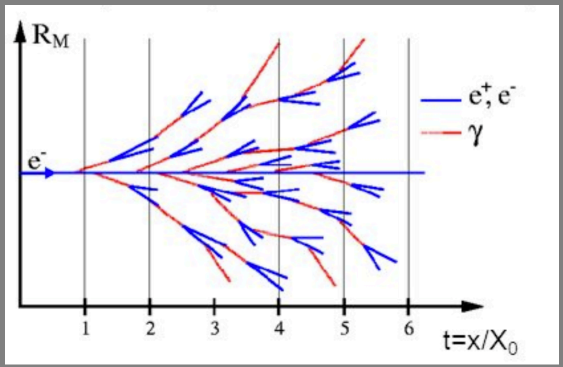


Brehm

Pair production

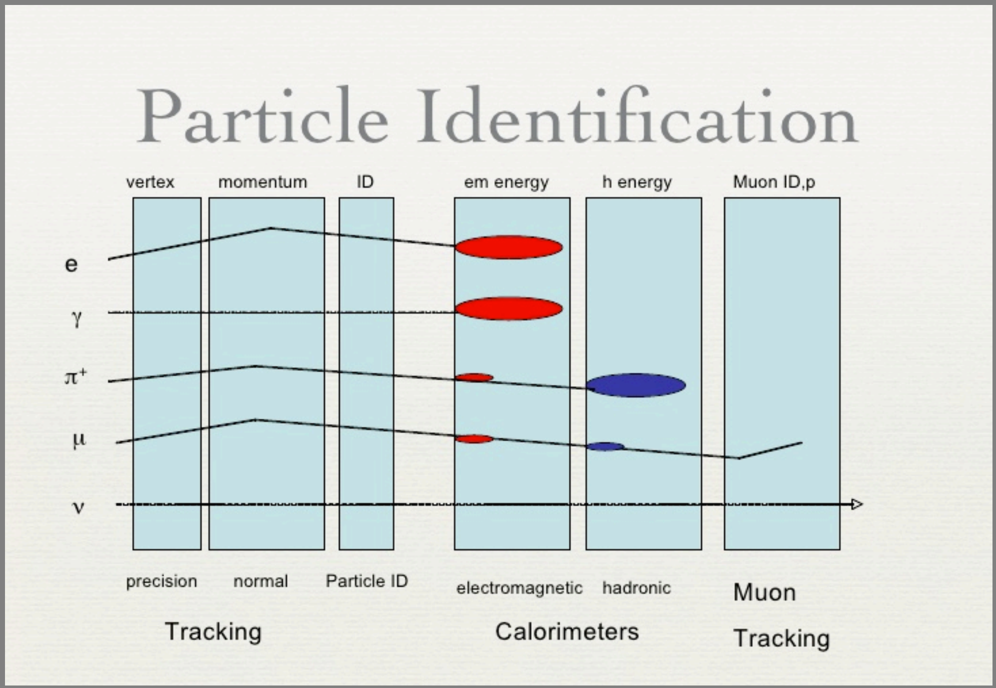
Shower

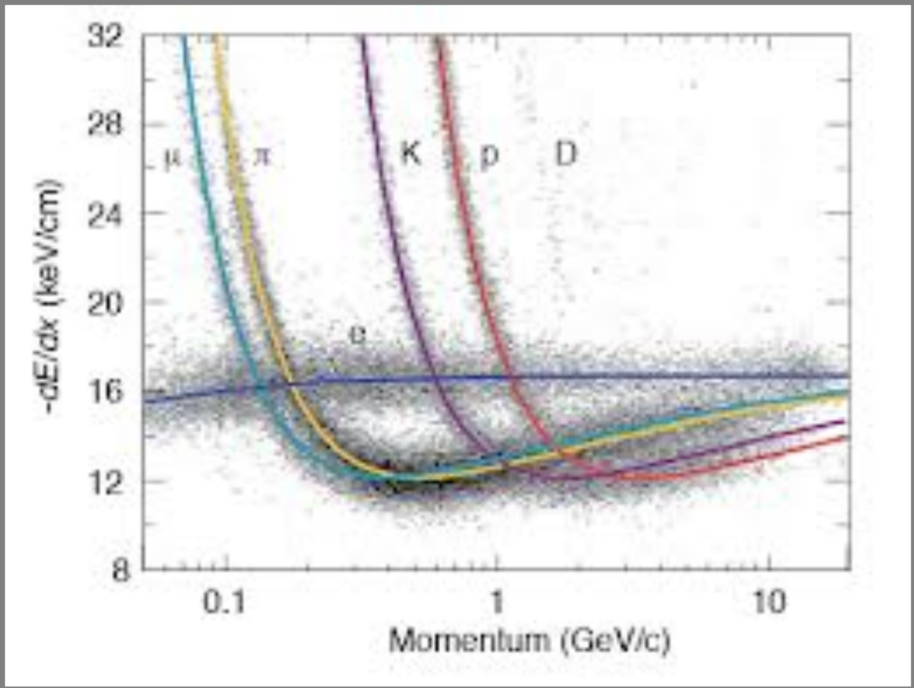
Plot dE/dx vs p=Mcβγ
Particle id

Not useful for high p

muons!

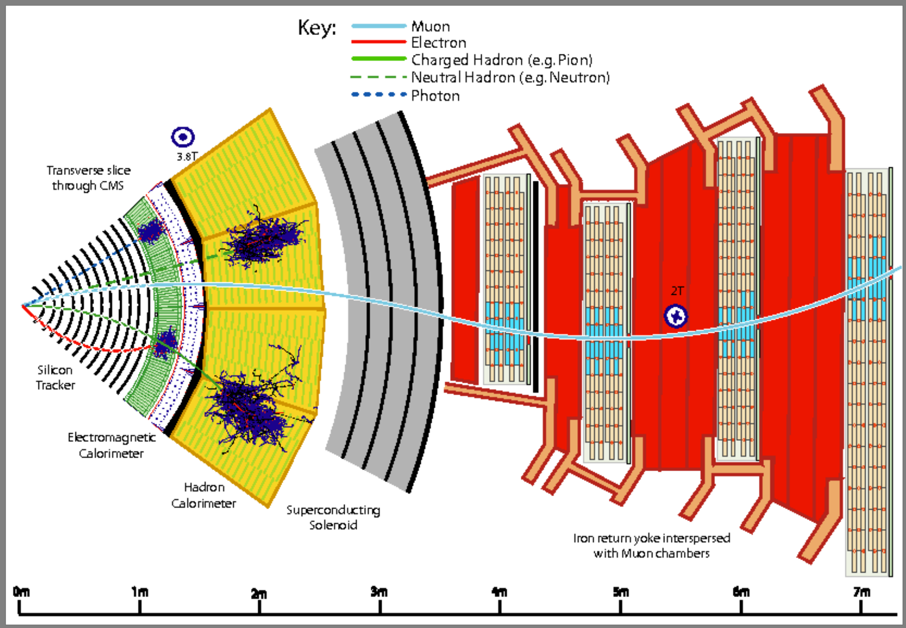
$\beta\gamma = p/mc$
If I know p, and βγ or dE/dx,
I know m.

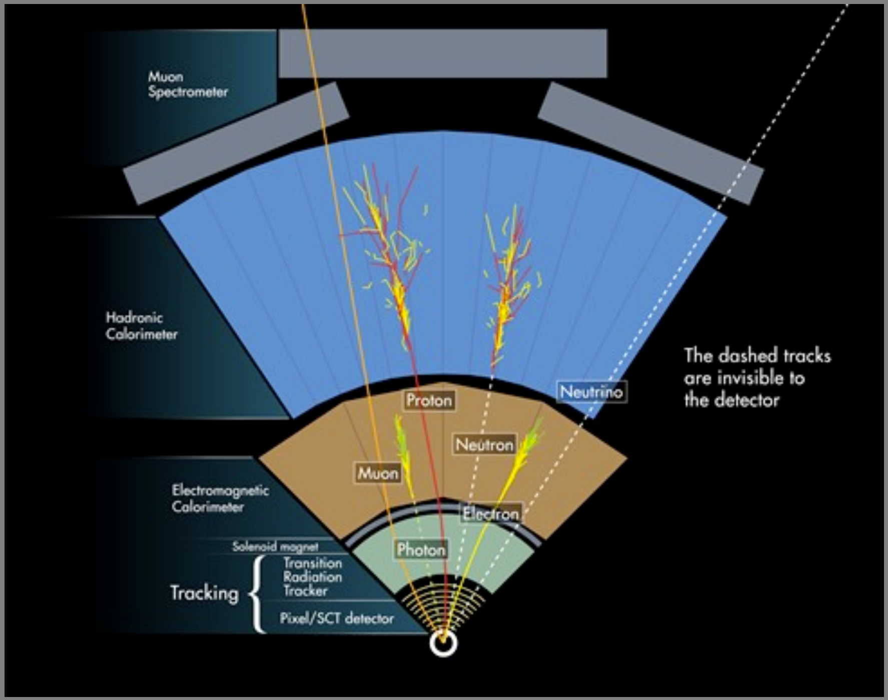




Measure muon momentum

- Need B fields precision detector, trigger.





-

Both ATLAS and CMS have an inner detector immersed in a solenoidal field and a Muon spectrometer with a B field - return field of solenoid for CMS -
Air core toroid for ATLAS
The combined resolution is best.

Flux return:

Flux return

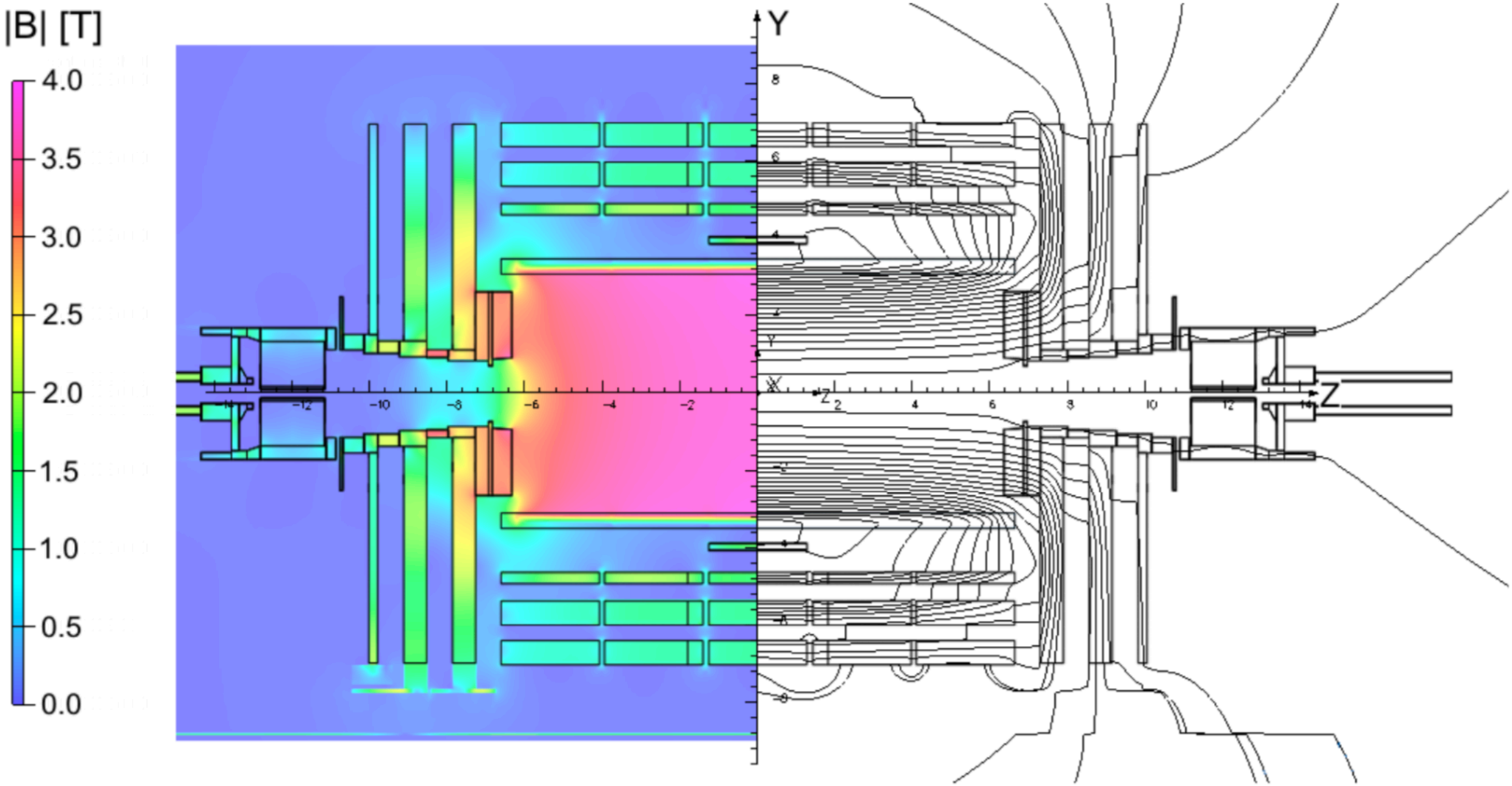
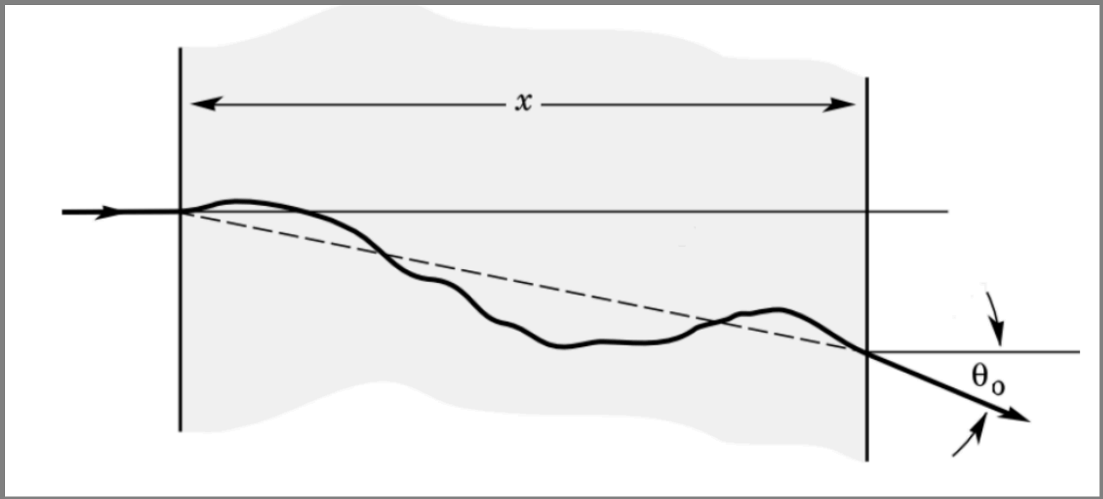


Figure 5: Value of $|B|$ (left) and field lines (right) predicted on a longitudinal section of the CMS detector, for the underground model at a central magnetic flux density of 3.8 T. Each field line represents a magnetic flux increment of 6 Wb.

Multiple coulomb scattering



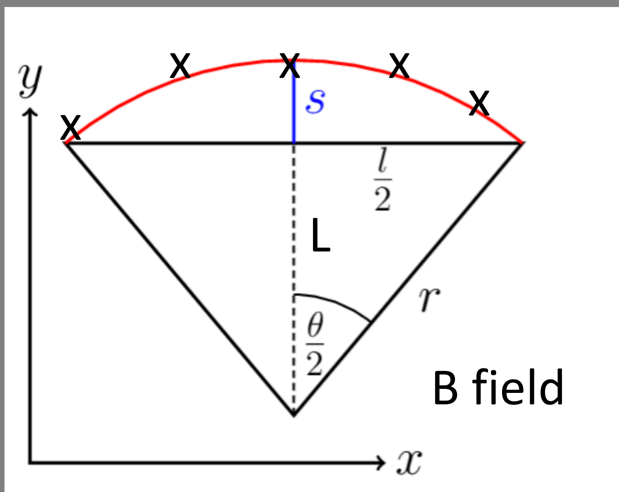
Like Rutherford scattering

$$\Theta_0 = \frac{0.0136}{\beta c p[\mathrm{GeV/c}]} Z_1 \sqrt{\frac{x}{X_0}}$$

Characteristic width of Gaussian

Measure sagitta s –> momentum resolution

- Recall p=qrB —>> p(Gev/c) = 0.3 R(m)B(T)



What is Δs? The uncertainty on s? σ_x /sqrt(N)
Where N is the number of measurements along L.

$$L = r\theta$$

$$s = r\left(1-\cos\frac{\theta}{2}\right) \sim \frac{r\theta^2}{8} = \frac{L^2}{8r}$$

$$r = \frac{L^2}{8s}$$

$$\Delta p = 0.3 B \Delta r = 0.3 \frac{BL^2}{8s^2}\Delta s$$

$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = \frac{\sigma_x}{\sqrt{N}} \frac{8p}{L^2 q B (0.3)}$$

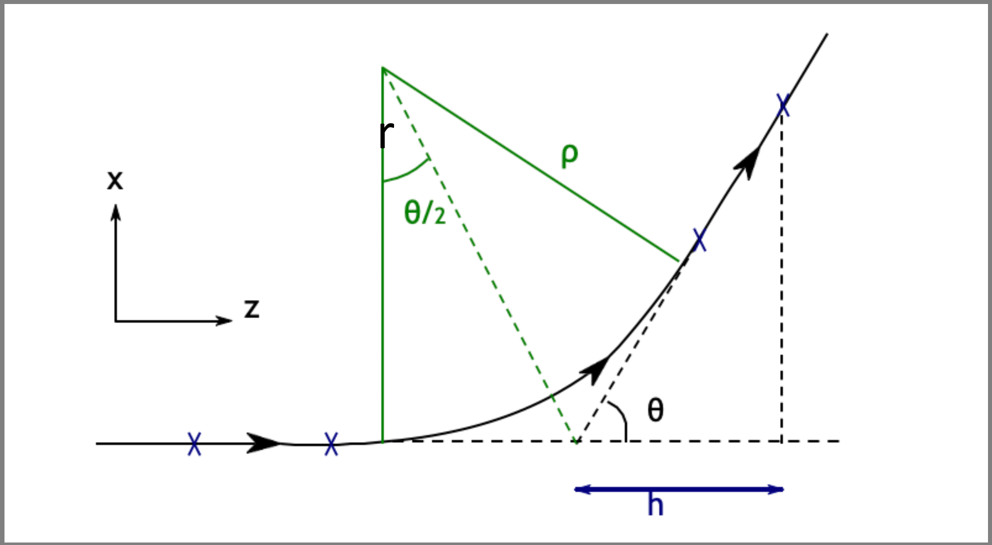
$$\Rightarrow \frac{\Delta p}{p} \sim p$$

Add multiple scattering to the resolution

Multiple scattering will change Θ a bit.

But $\Theta = L/r = 0.3\, B\, L/p$

$\Delta p/p = \Delta\,\Theta/\Theta = \Theta_0/\Theta$



$$\left(\frac{\Delta p}{p}\right)_{MS} = \frac{\Theta_0}{\Theta} \sim \frac{.04}{\beta L B}\sqrt{\frac{L}{X_0}}$$

X_0 - radiation length

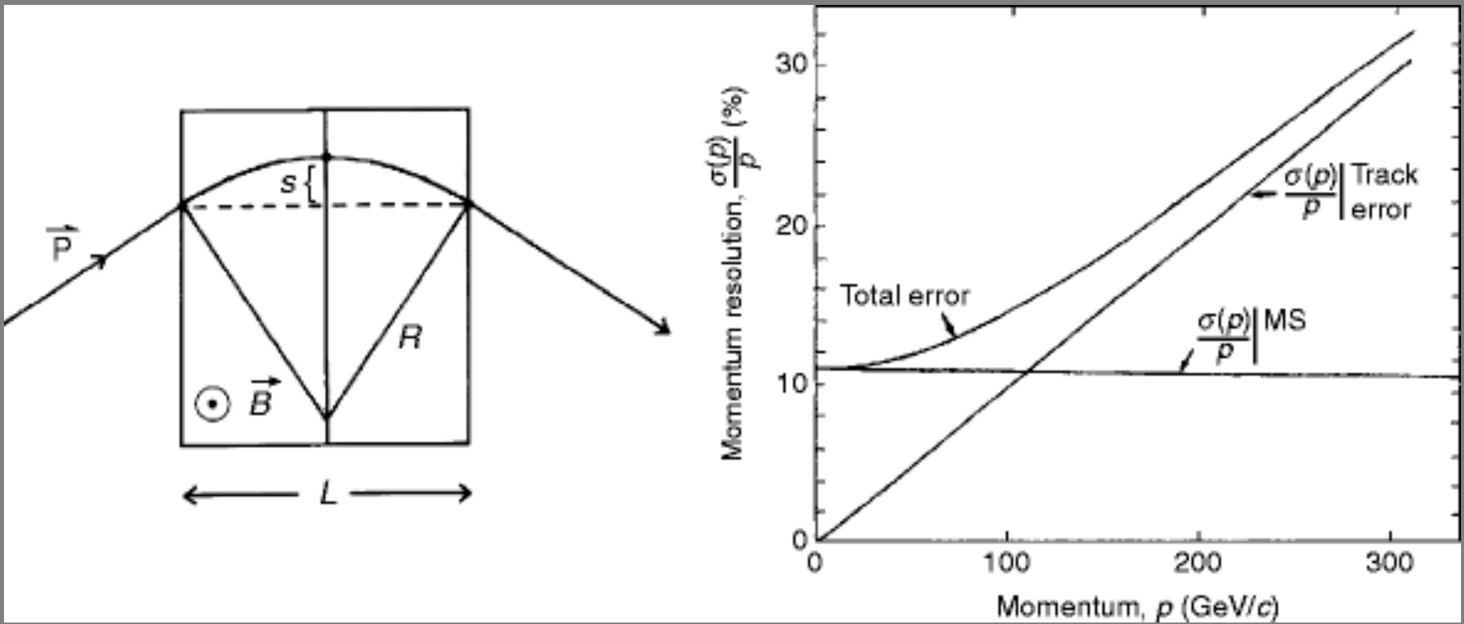
Independent of p!

Momentum resolution

The contribution due to MS is constant with momentum!
And gives the limit for low p. The contribution from the position measurement

$$\left(\frac{\Delta p}{p}\right)_{total} = \sqrt{\left(\frac{\Delta p}{p}\right)^2_{Sagitta} + \left(\frac{\Delta p}{p}\right)^2_{MS}}$$

multiple scattering

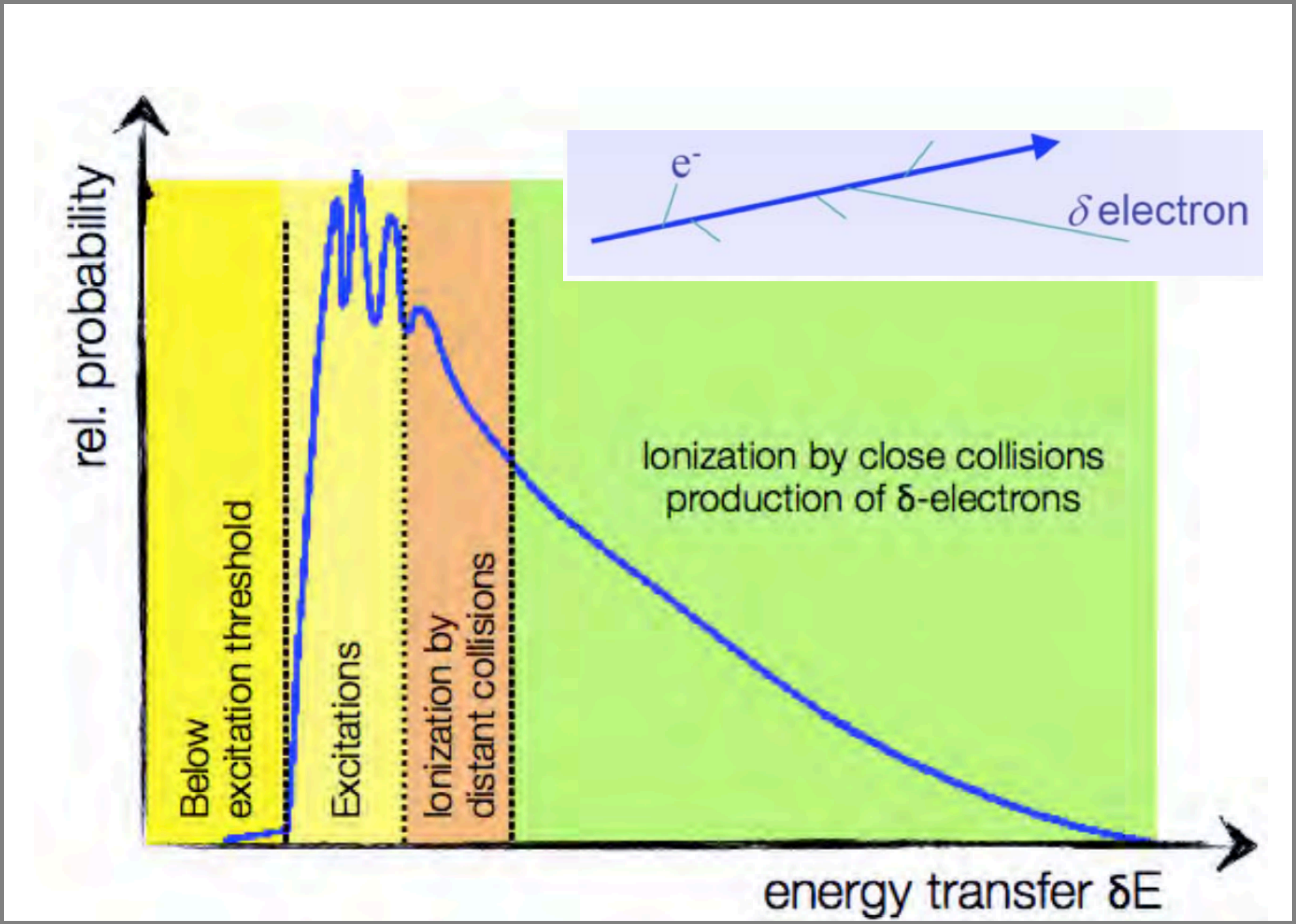


If you consider a 100 GeV muon -

Traversing 1m steel gives Θ_0 ~ 4 mrad or 4mm over a meter

Traversing 1 m of air gives Θ_0 ~0.02 mrad or 20 microns

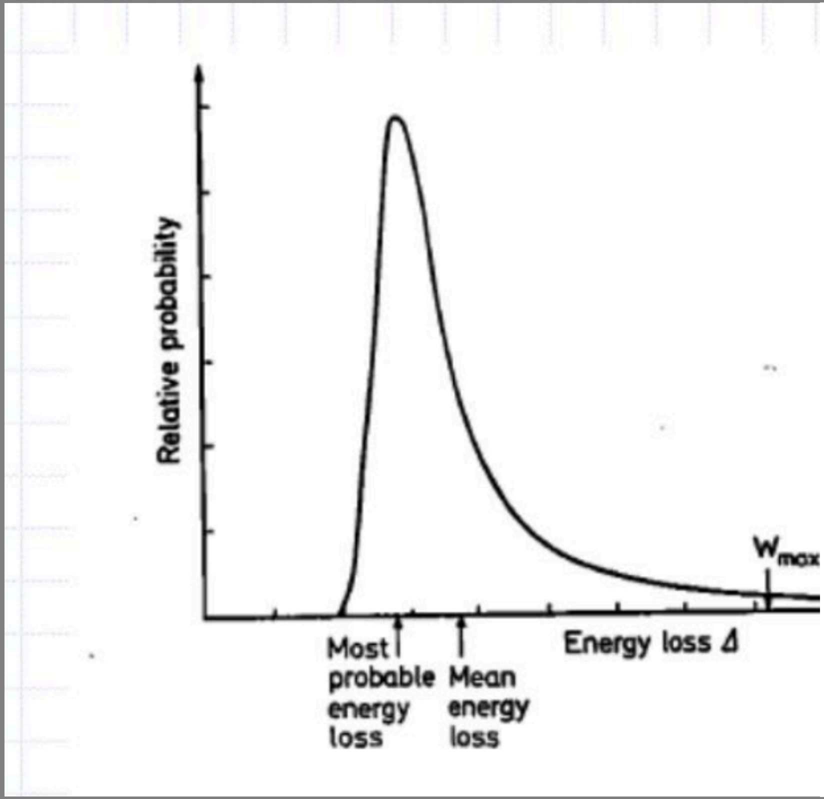
Energy loss fluctuations in material affect our measurements

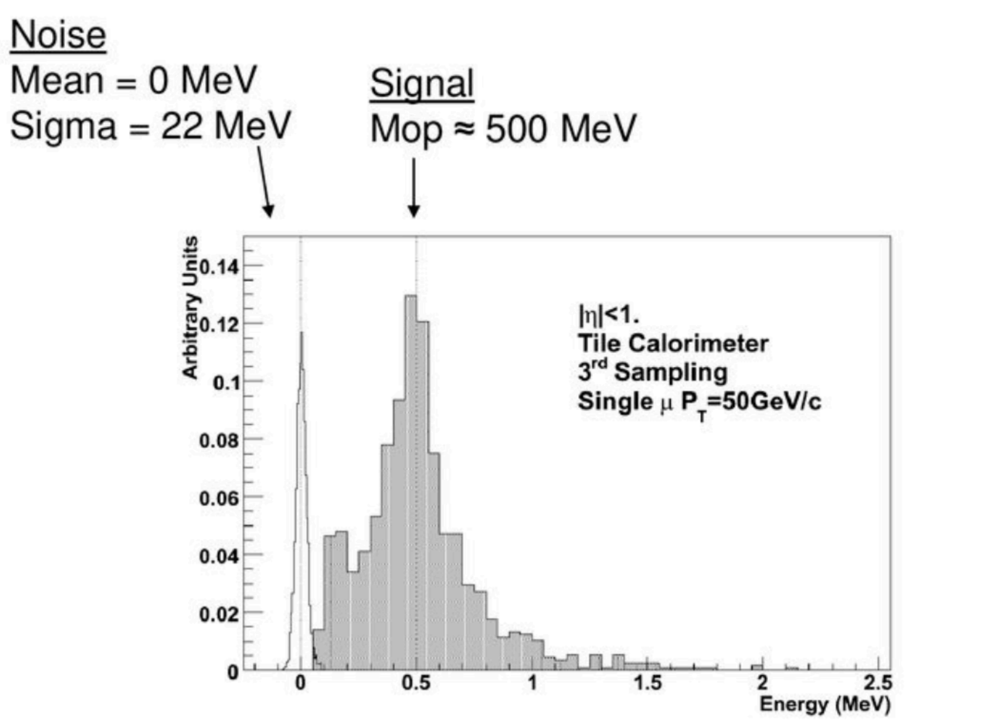


Especially at low momentum

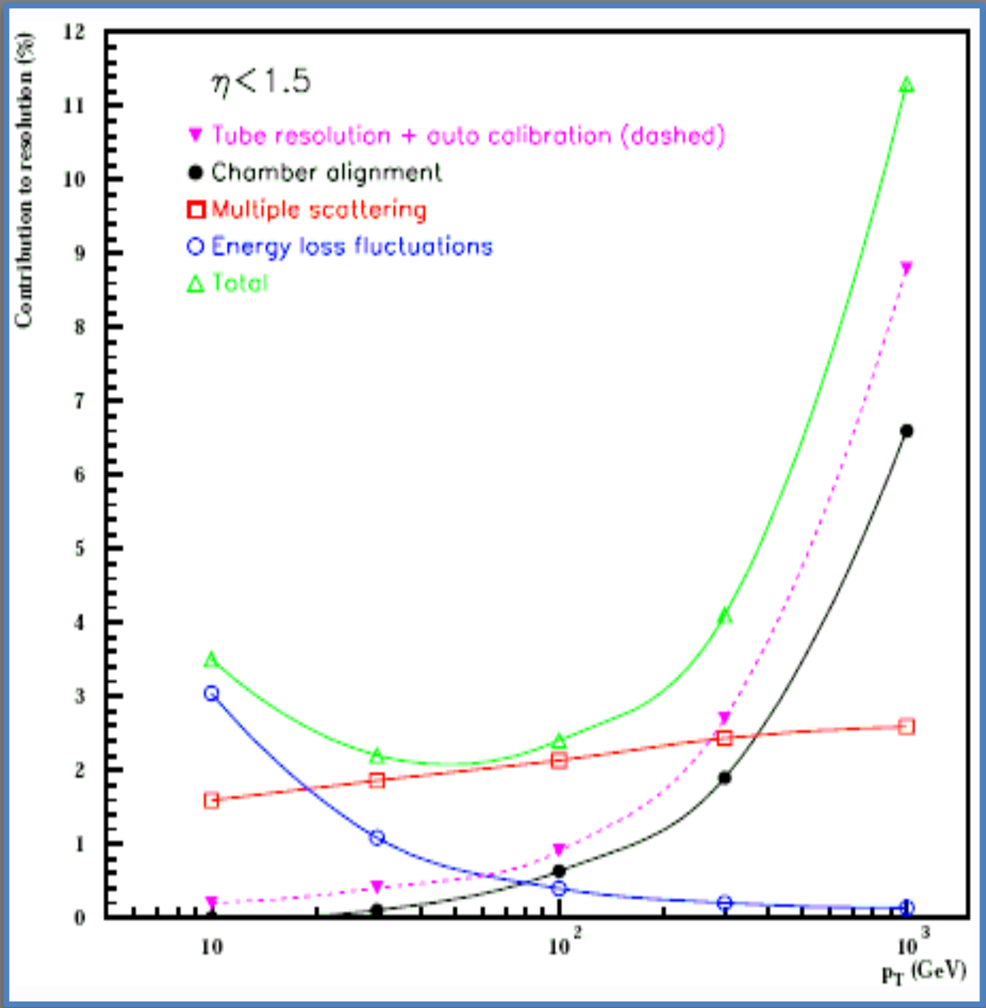
Energy loss distributions

B-B is average energy loss, there are fluctuations due to close collisions. Muon leaves minimum ionizing deposit in calorimeter





Momentum resolution



ATLAS vs CMS Muon resolution

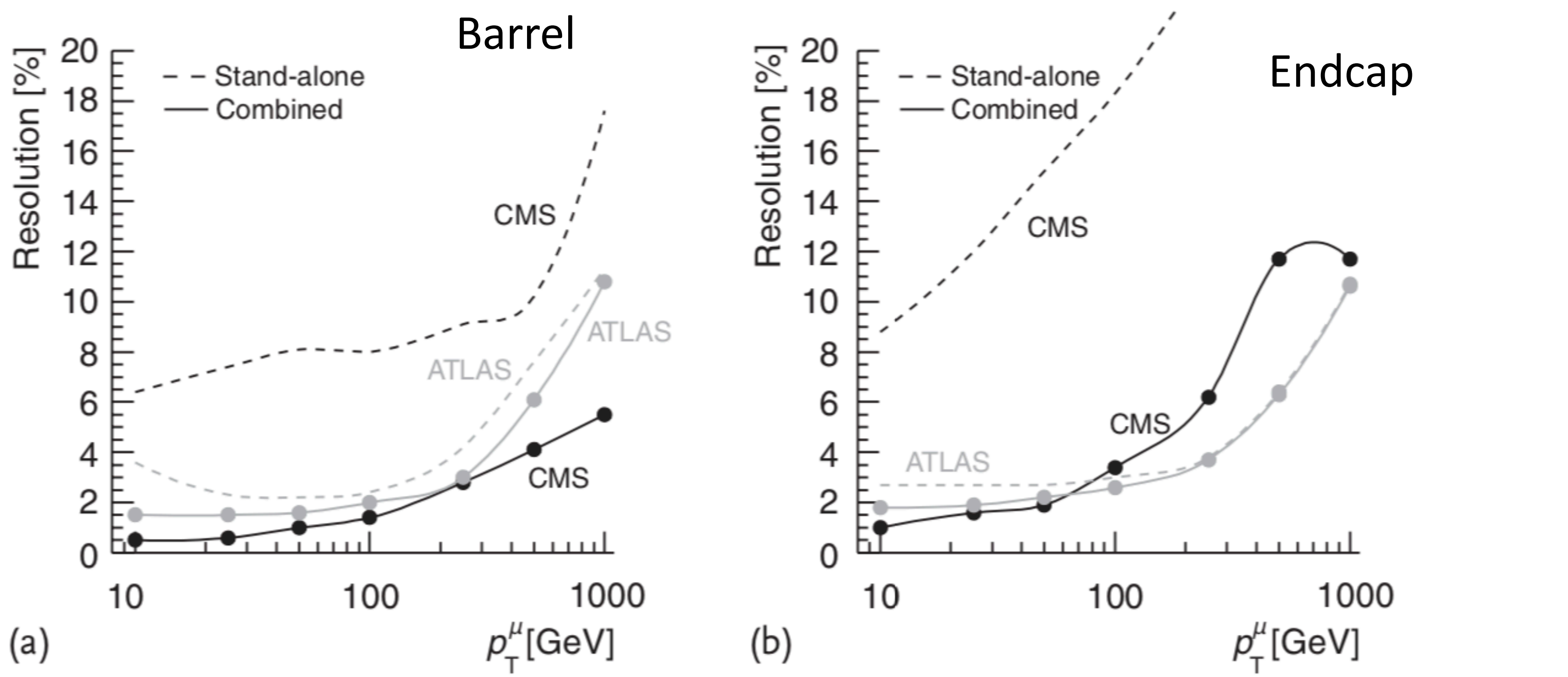
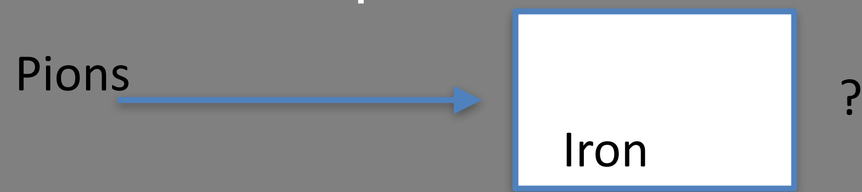
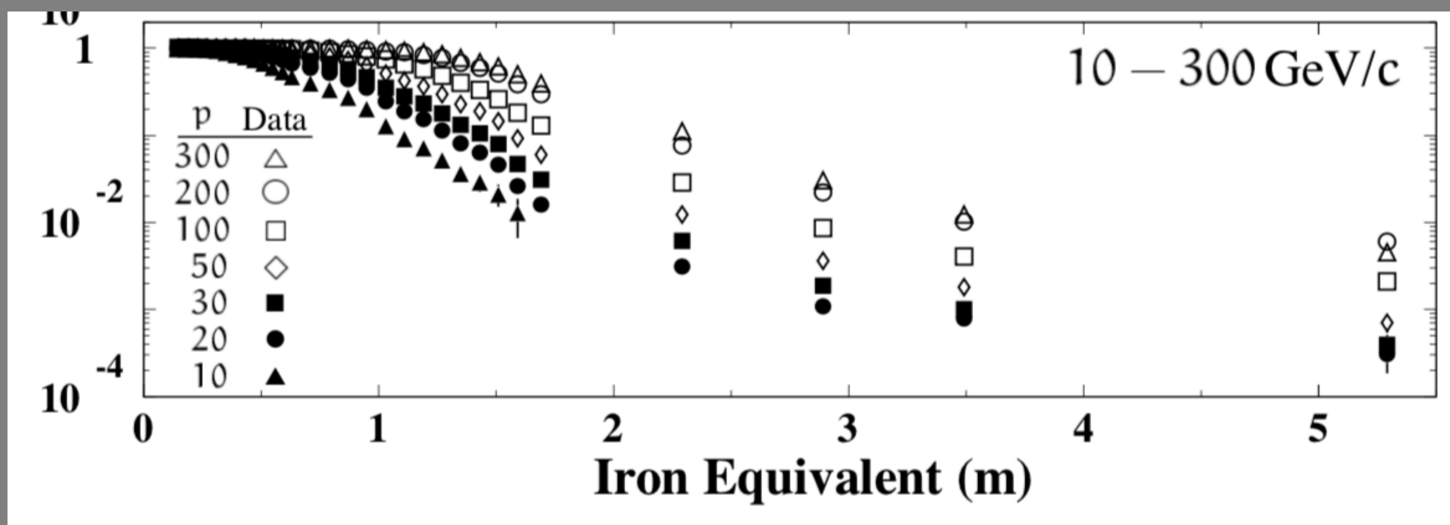


Figure 16.4 Momentum resolution of the ATLAS and CMS detectors after combining the momentum measurements of the inner (a) momentum resolution for muons in the barrel region; (b) momentum resolution for muons in the endcap region.

Pion punch through

When does a pion look like a muon?





Pion Punchthrough probability - RD5

Why talk about resolution and punch through

We need to design the next pp experiment at the FCC

We can measure the track Sagitta in the inner detector

We can measure the bending of the track after the magnetic field coil.

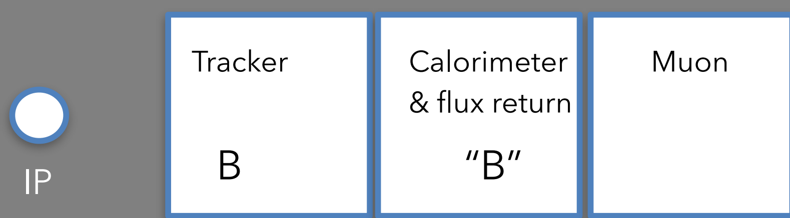
We can measure the Sagitta in the instrumented return yoke

We can measure the muon independently after the calorimeter in a dedicated muon spectrometer with its own magnetic field

What should we do?

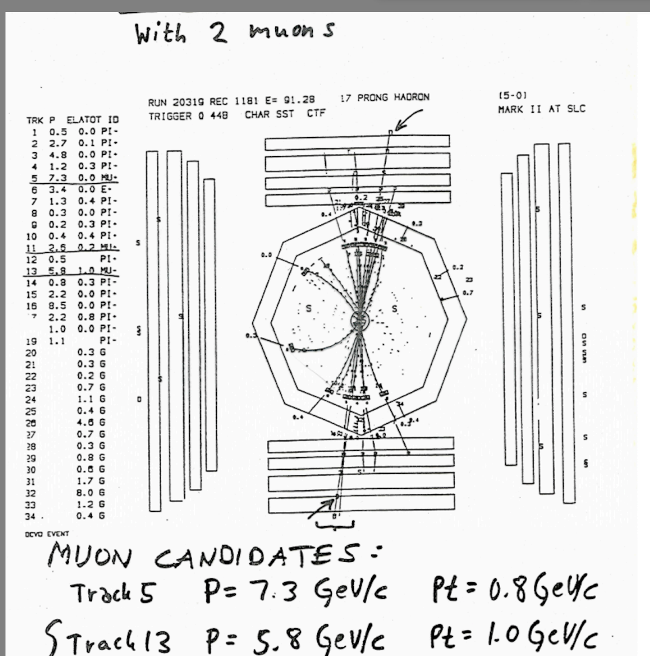
Why talk about resolution

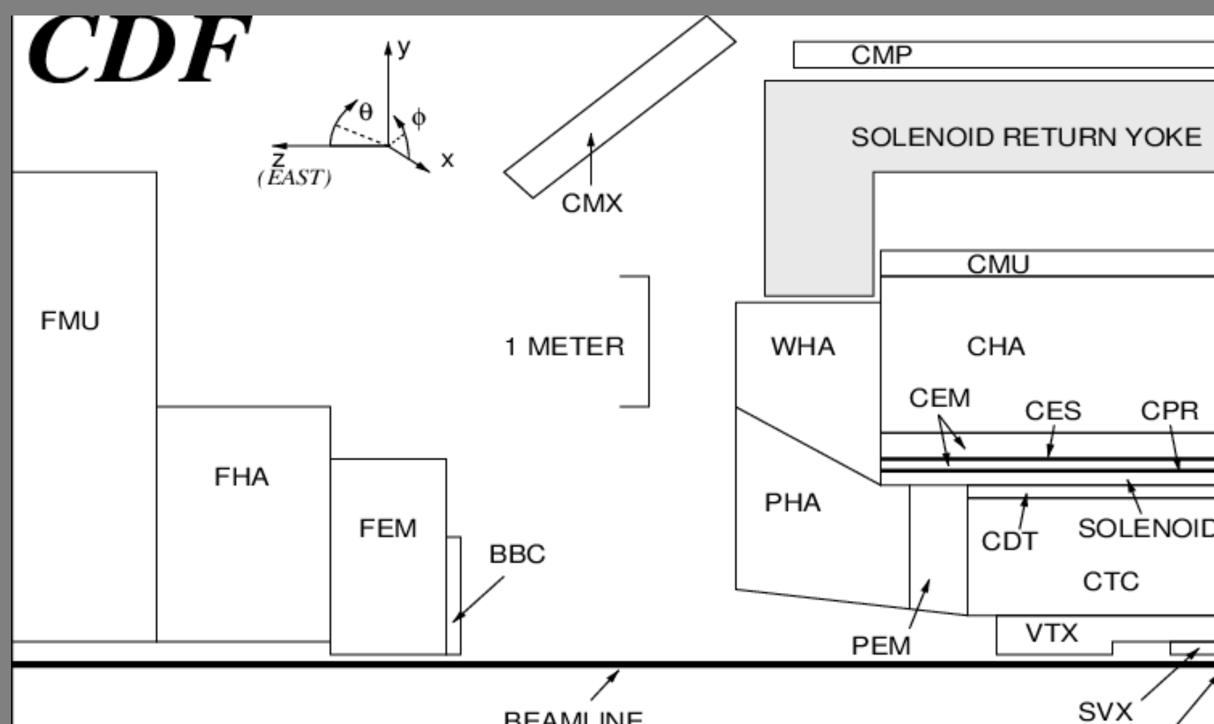
It will help design the next experiment.



Use muon detector to tag muons

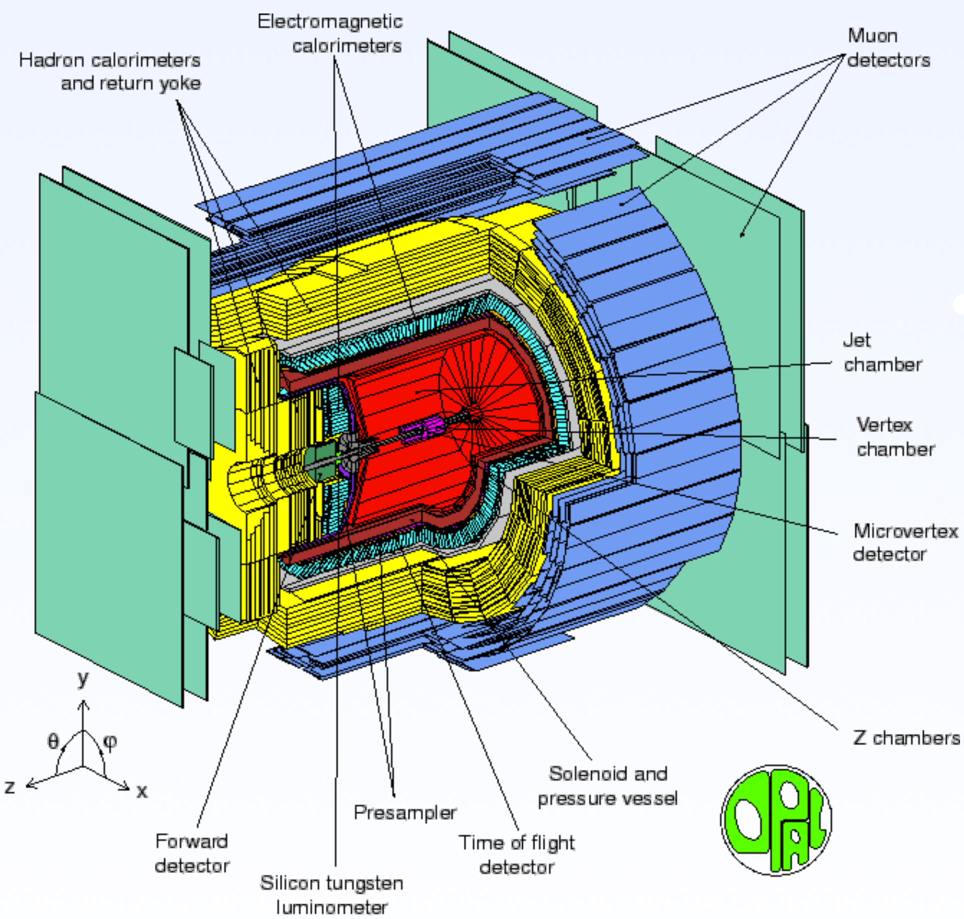
SPEAR

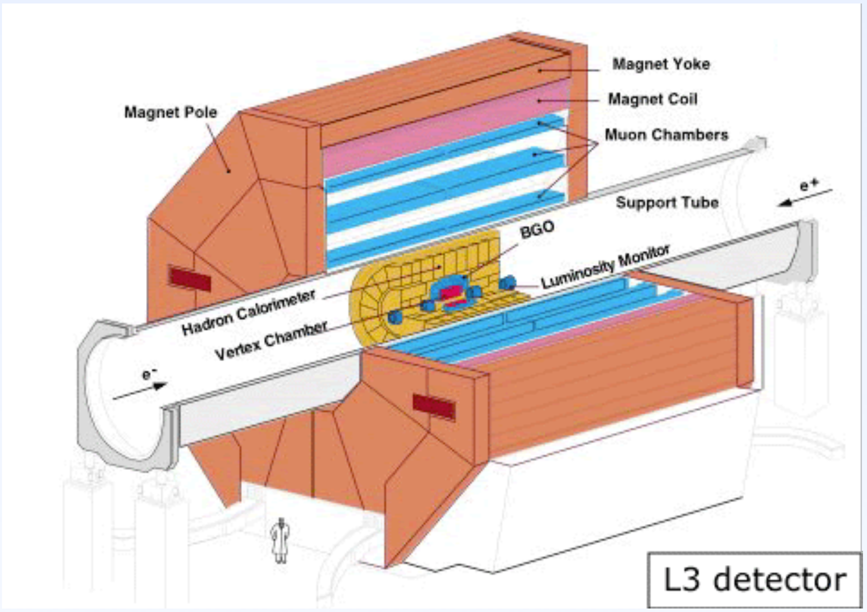




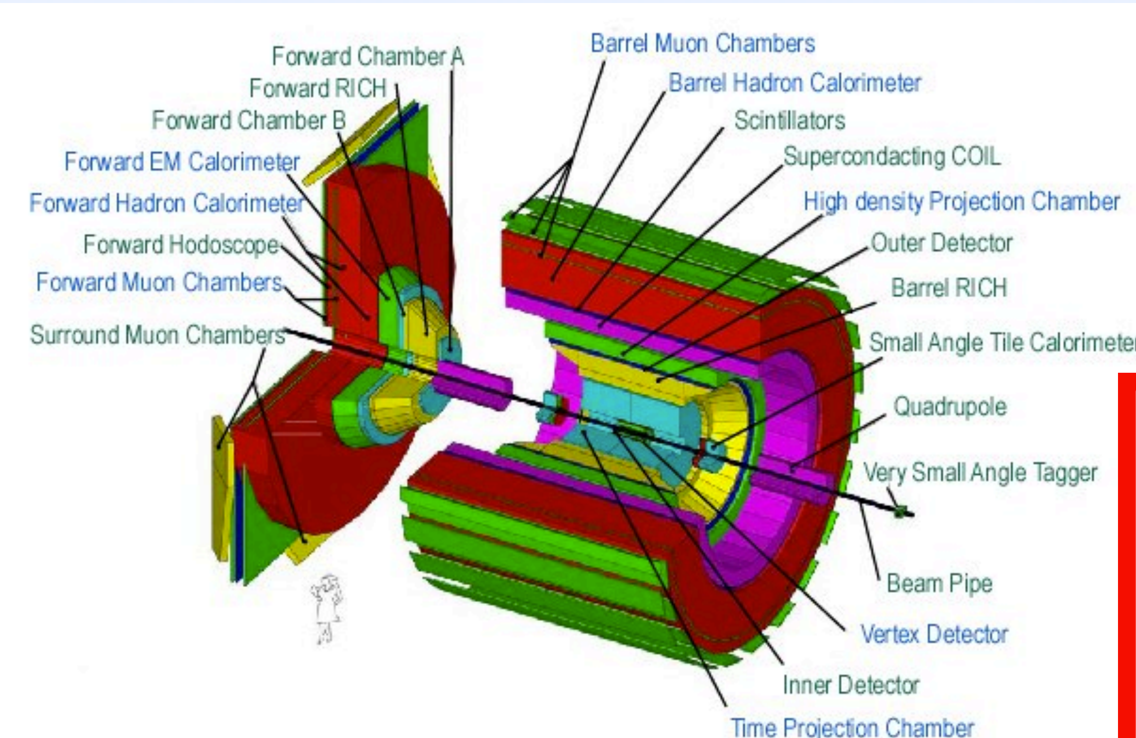
LEP experiments. e+e-

OPAL

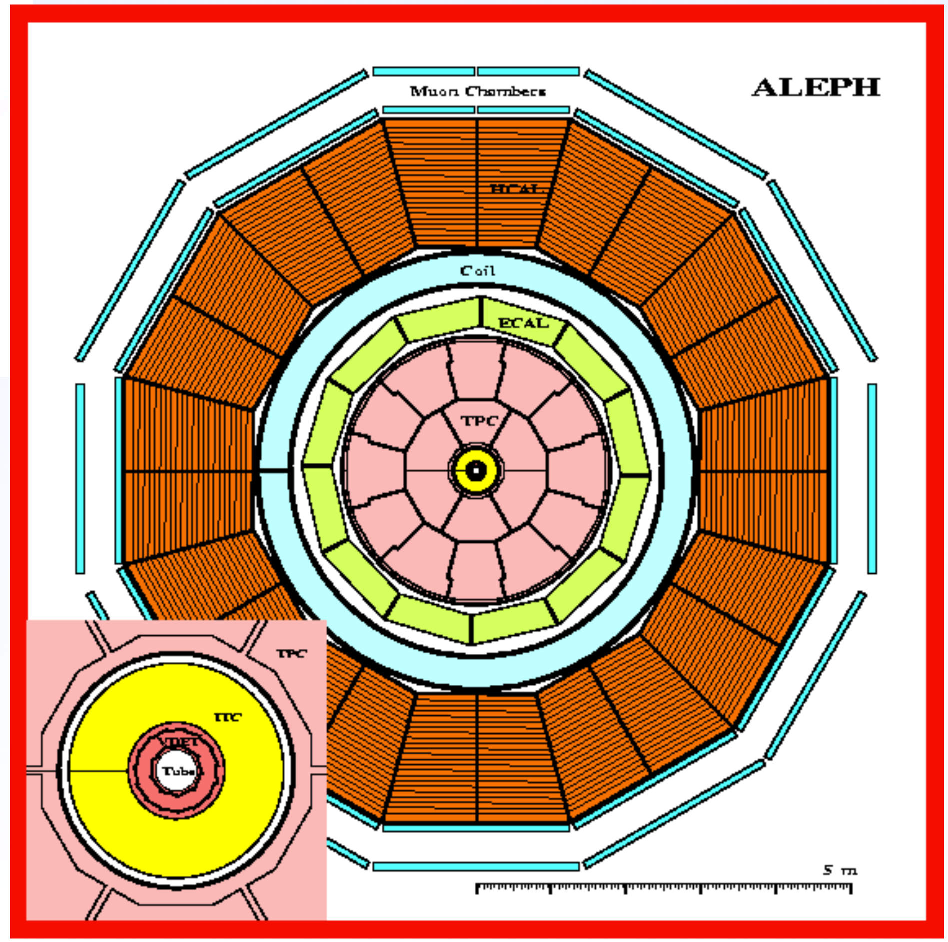




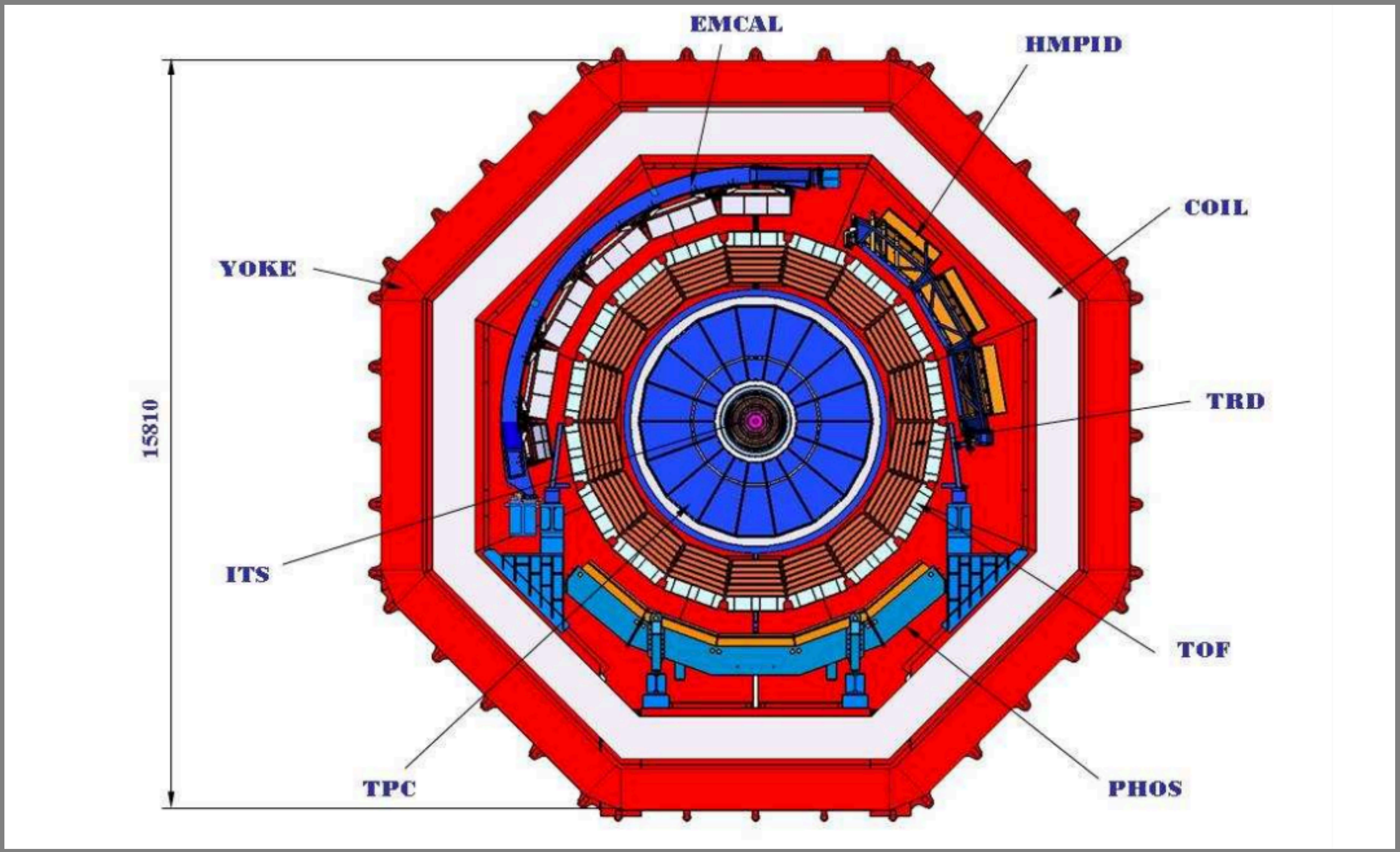
LEP detectors



Delphi

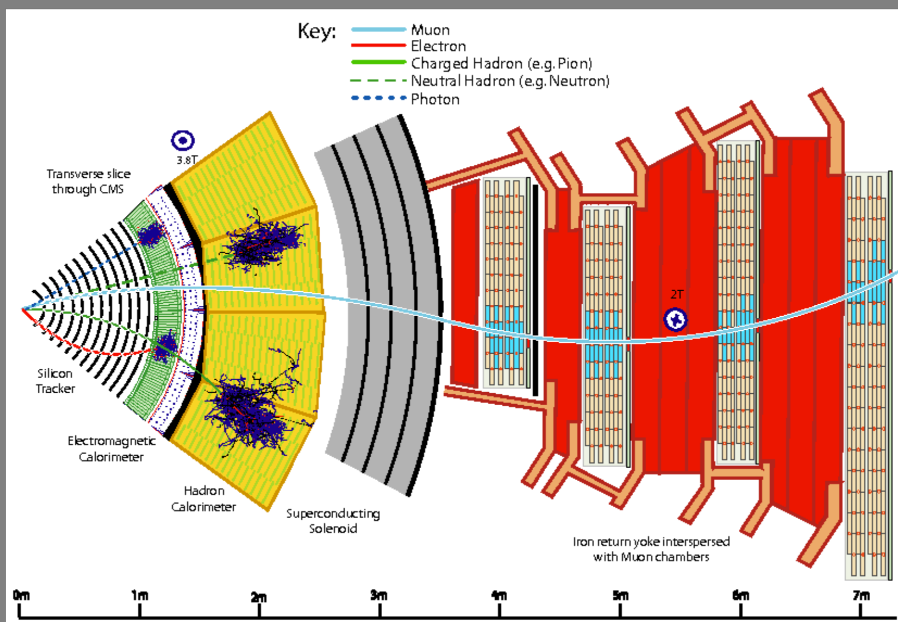


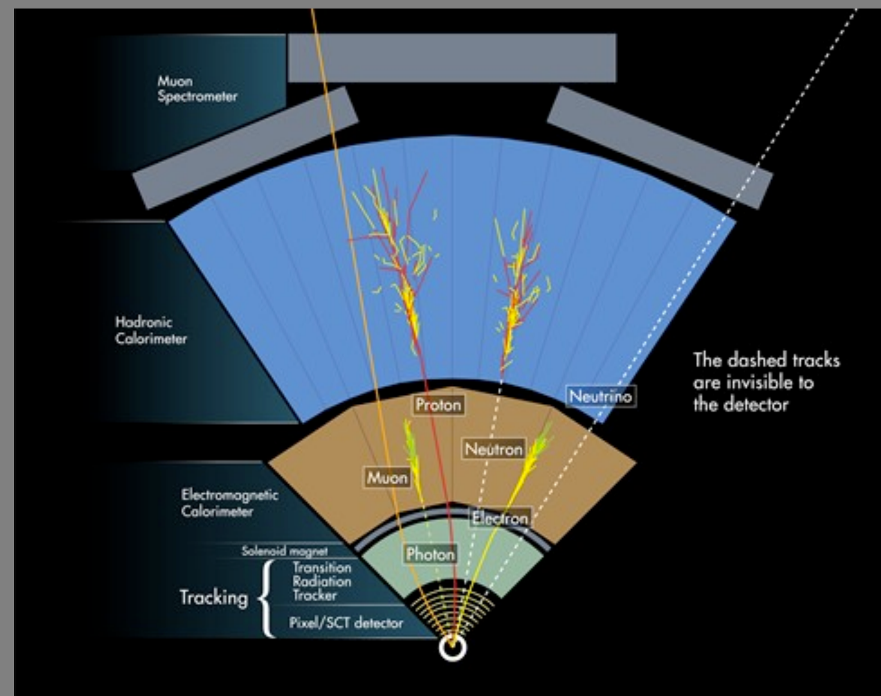
ALICE detector for heavy ion collisions



Central detector has no muon detection

- Need B fields precision detector, trigger.

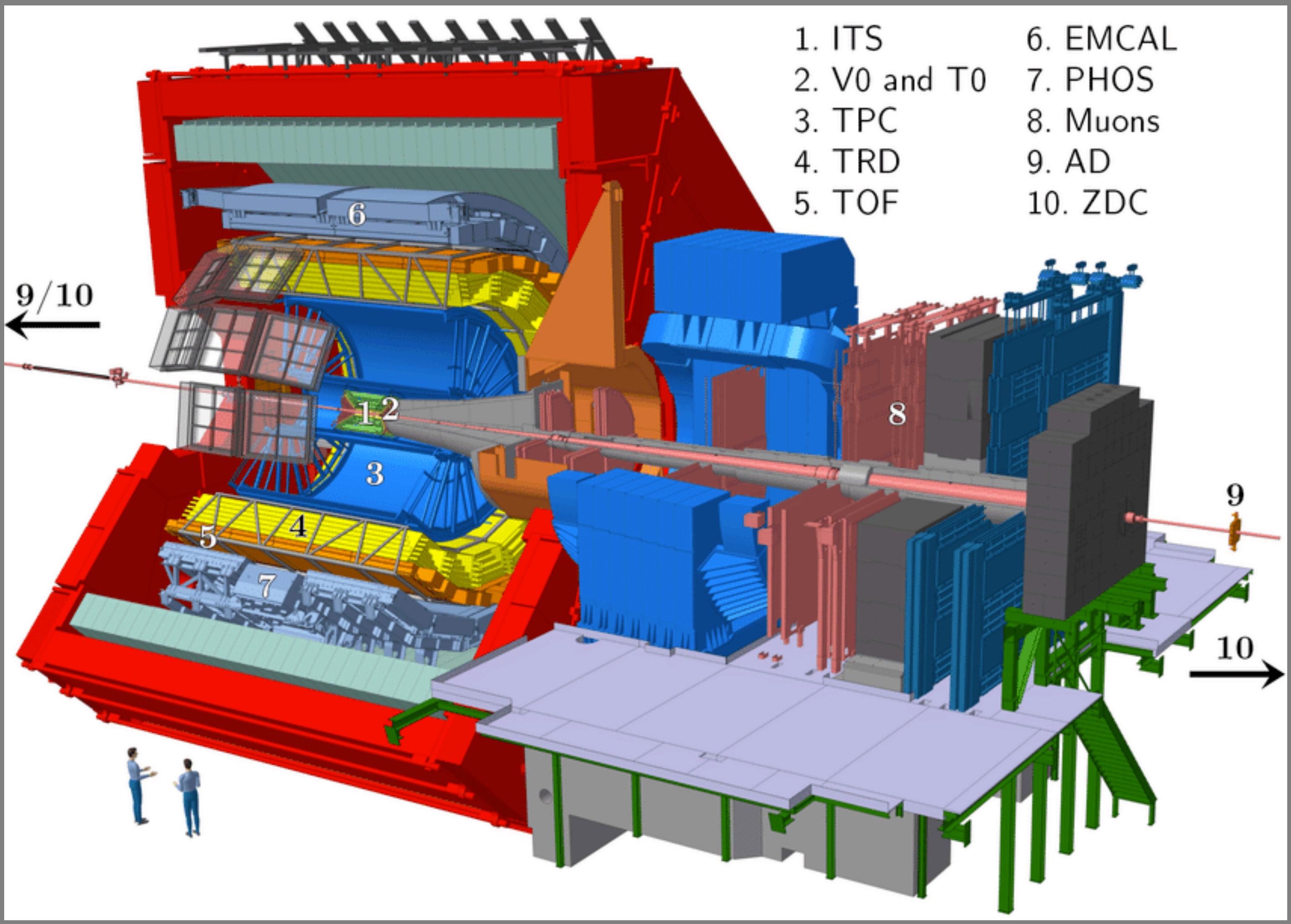




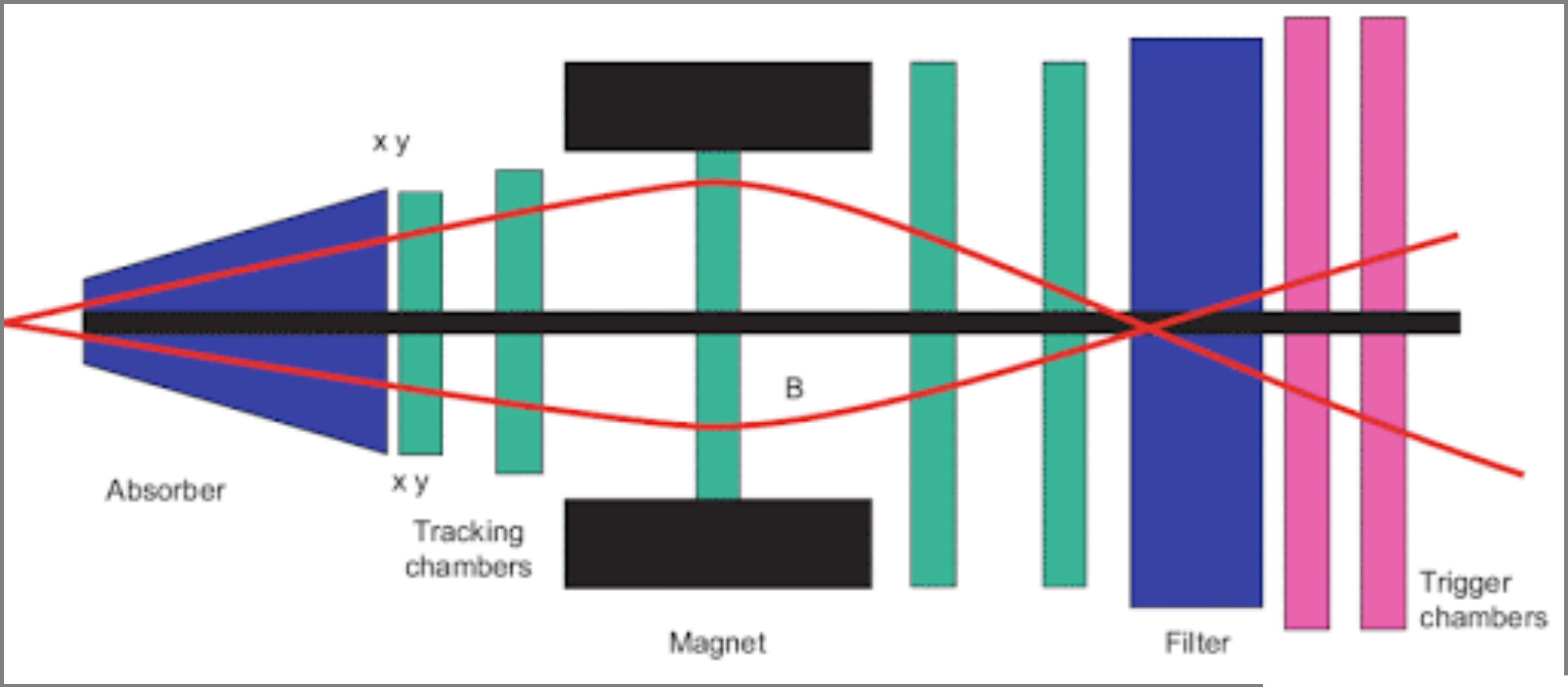
-

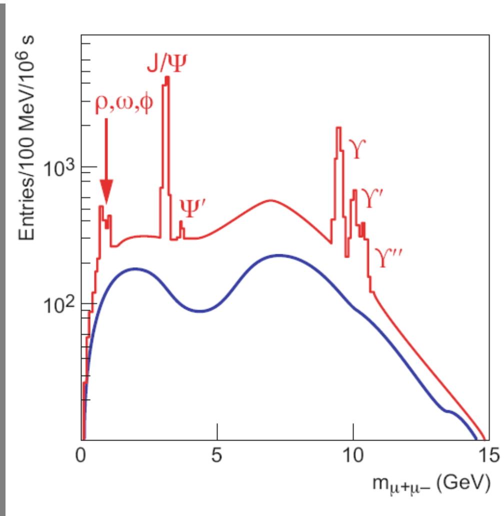
Both ATLAS and CMS have an inner detector immersed in a solenoidal field and a Muon spectrometer with a B field - return field of solenoid for CMS -
Air core toroid for ATLAS
The combined resolution is best.

ALICE dedicated solid angle for muon detector



ALICE muon spectrometer - dipole magnet





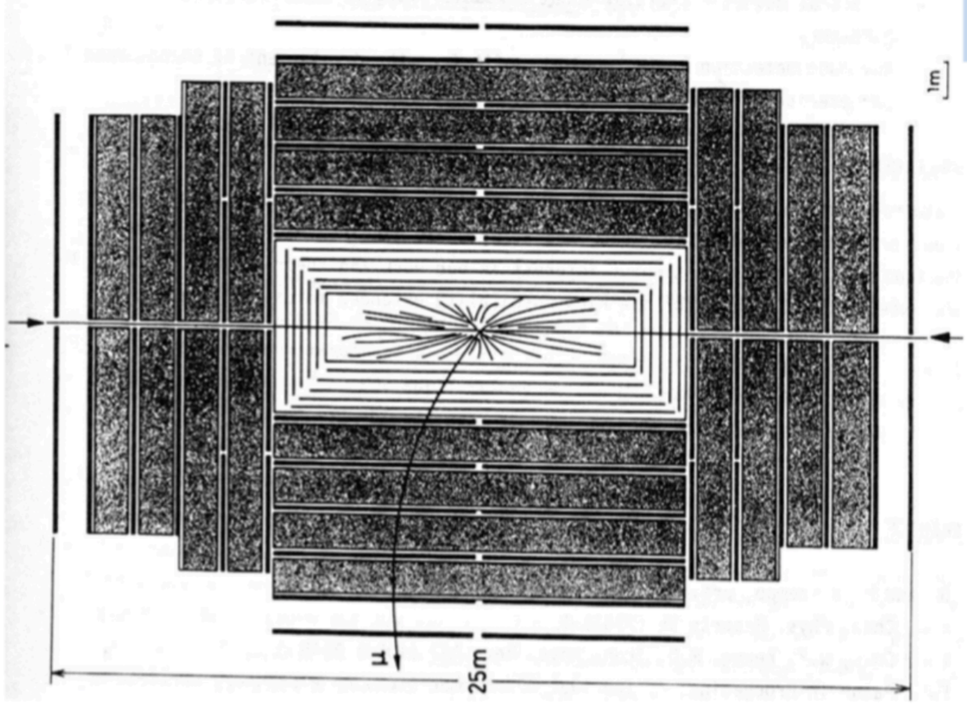
Mass spectrum.

First thoughts on an LHC detector

Detectors discussed at Lausanne

- 221 -

1984

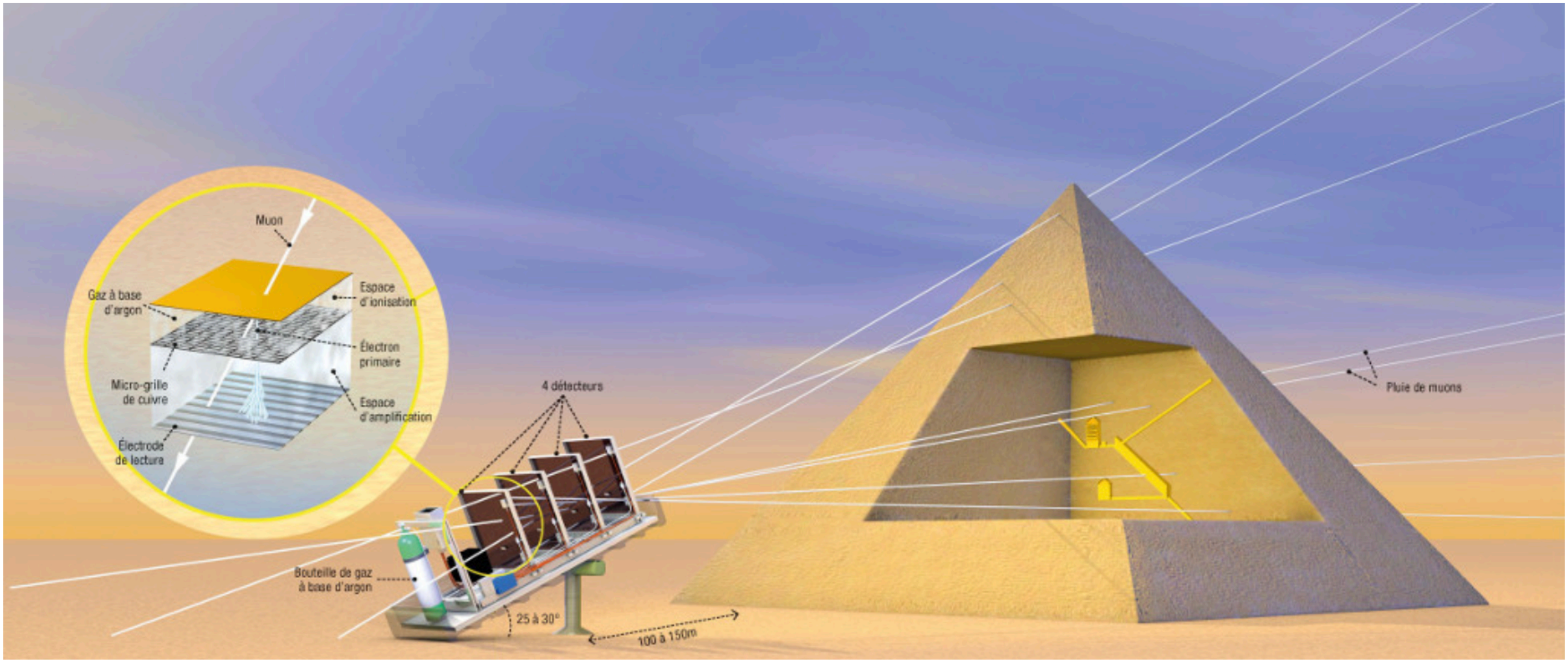


- Magnetized Iron ball
- Tracking a la « UA1 »

Look for missing matter

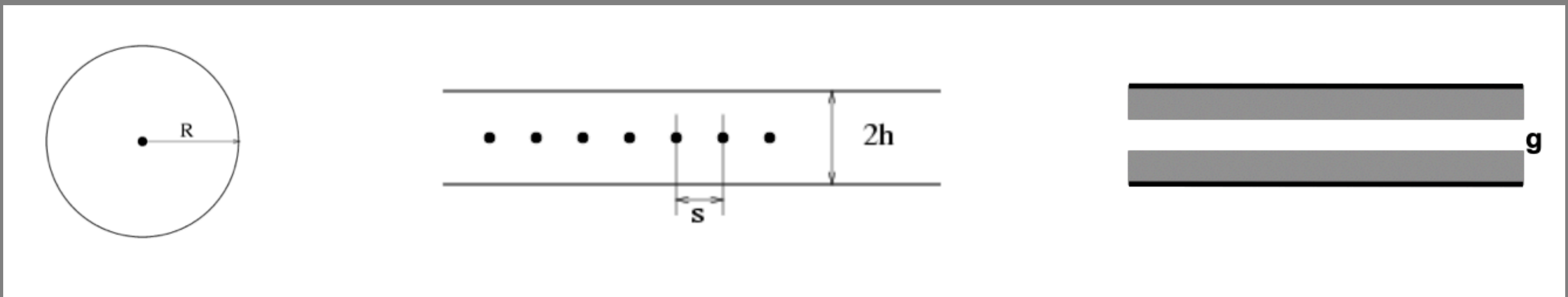
#ScanPyramids project

15 December 2016



With micromegas detectors! Tomorrows lecture.

Tomorrow: Muon detectors I have known and weird problems they have had and New detector technologies.



This is what we have now - drift tubes, RPC’s, CSC’s, TGC’s
What’s next?